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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Model-based offline planning for dual-arm robotic manipulation of deformable linear objects

Laurea Magistrale in Automation and control Engineering - Ingegneria dell'automazione

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1. Introduction

Deformable Linear Objects (DLOs) are elements, like wires, hoses and ropes, with one dimension that is larger than the other two: for this reason they are highly prone to shape deformations.

Interest in robotic manipulation of deformable linear objects is growing rapidly, but, despite the high necessity of manipulating this kind of objects, the handling of DLOs is usually performed manually, due to the several issues in automatising this tasks. This leads to a bottleneck in industrial frameworks. The main challenges are related to the highly non-linear behaviours and the large number of degrees of freedom to deal with, leading to complex models, and limiting sensors applications, such as vision sensors and force sensors.

For this reason, all the available information about the DLO and the environment should be used, in order to globally estimate the behaviour of the DLO during the operation.

This work proposes a model-based offline methodology to plan a dual-arm robotic manipulation of a deformable linear object. The planner is based on an already existing dynamical model of the cable, and aims to bring the DLO from an initial shape to a desired one. An optimization-based planning is implemented to find a series of intermediate shapes for the cable, and then the trajectories for the robot grippers holding the ends of the DLO are extracted. A simulation environment is provided to better inspect interaction with the environment and obstacles, and a re-optimization strategy is implemented for obstacle avoidance purposes. An algorithm for the Young's modulus identification is developed, in order to inspect stiffness properties even for composite cables, and to be able to properly initialize the dynamical model.

Finally some tests are performed to validate the method, and an industrial wire harness assembly application is carried out with the developed algorithm.

2. State of the art

Due to the difficulty of modeling DLOs, different models have been studied in the past.

The finite element method (FEM) [4] allows to create a very accurate model, but heavy computations have to be solved. Another strategy is to regard them as tiny elastic rods: a method is the *Kirchoff elastic rod*, exploited in [1], or the *Casserat model*, used in [3]. However us-

ing such models for optimization and simulation can be challenging, because of the over complexity introduced. The *mass-spring model* is a simple but informative model for deformable objects: it is composed by mass-points and various springs. The model was firstly introduced by Humann and Parant [2], additional contributions are given by Look et al. [5] and also by Lv et al. [6], leading to a complete model, representing axial, bending and torsional behaviours through different kinds of springs.
Due to the complexity of the models describing deformation behaviours of DLOs, few works in literature deal with the planning of paths for robot manipulating these objects. In [9], Sintov, Macenski et al. developed a planning strategy by modelling a DLO as an elastic rod. However the strategy involves a heavy computation for the solutions of the model, related to the search of equilibria and stable configurations. Additionally, the planning is based on the forces applied by the grippers, involving the necessity of reliable force sensors. Moreover the strategy focuses on stiff cables, considering inextensible rods and neglecting gravity forces.
In [7], a geometrical model is exploited, and an adaptive segmentation of the DLO shape is developed, based on the complexity of the configuration. An additional work must be done in order to relax the assumption of constant length, and in order to introduce a more reliable model providing energy associated to the curve. Moreover this solution introduces a degree of complexity, expanding the research of minimal energy curves with the problem of determining the optimal representation for such curves.
Roussel et al. [8] provided a solution for the planning problem of an extensible elastic rod in free or contact space by working with the integration of two models: an elastic rod model and a FEM-based dynamical simulator. This solution exploits two computationally heavy models, introducing the additional complexity of combining the two different environment.
Finally, in [10], Zhu et al. proposed a framework that allows robots to use contacts with the environment in order to shape DLOs, limiting the strategy to soft-cables, involving a model-free solution and managing only 2 dimensional problems.

Thesis contributions

The main contributions of this work are: (1) The exploitation of an easier but still informative model such as the mass-spring model, for an efficient integration of a model-based optimization and a simulation environment, including axial and bending forces, torsional behaviours and gravity effects (2) The combination of a decoupled geometrical optimization and a physical one, based on the internal forces of the DLO (3) The implementation of a Young's modulus identification for composite cables, and an adaptation mechanism that allows to work with DLOs of various kinds of stiffness.

3. Model

The model exploited in this work is the mass-spring model. Geometrically, the DLO is represented as a sequence of $\mathbf{n+1}$ mass-points connected by $\mathbf{n}$ straight lines, called links. The total mass m^o is distributed along the cable through mass-points: $m_i = m^o/(n+1)$. The initial total length of the cable is l^o, and the initial length of each link is $l_i^0 = l^0/n$. Axial springs, bending springs and torsional springs are associated to each link, introducing the dynamical aspects related to the DLO, as shown in Figure 1.

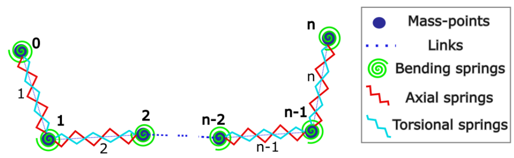


Figure 1: Mass-spring model.

Position coordinates $(x_i, y_i, z_i)^T$ are associated to each mass-point, and a torsion angle ψ_i is associated to each link.
By exploiting the Newton's second law the equations of motion can be computed:

$$m_i \frac{\delta^2 \boldsymbol{x_i}}{\delta t^2} + k^d \frac{\delta \boldsymbol{x_i}}{\delta t} = \boldsymbol{F_i} = -\frac{\delta U}{\delta \boldsymbol{x_i}} + \boldsymbol{F_i^e} \qquad (1)$$

where k^d is a fictitious damping coefficient, introduced to prevent oscillating behaviours, $\mathbf{F_i}$ is the force acting on each mass-point, it can be divided in some internal forces $\mathbf{F_i^i}$ and external forces $\mathbf{F_i^e}$: $\mathbf{F_i} = \mathbf{F_i^i} + \mathbf{F_i^e}$
The internal forces can be computed starting from the energy associated to the DLO: U is the total potential energy of the spring system. $U = \sum_{i=1}^{n} U_i$, and U_i is the energy associated

to a single link. Each term U_i takes account of the energy introduced by linear, bending and torsional springs: $U_i = U_i^s + U_i^b + U_i^t$.

$$U_i^s = \frac{1}{2}k_s(l_i - l_i^0)^2, \quad U_i^b = \frac{1}{2}k_b\beta_i^2, \quad U_i^t = \frac{1}{2}k_t\psi_i^2$$

where k_s, k_b and k_t are the stiffness coefficients associated to each spring. These stiffness coefficients depend on the Young's modulus and the Poisson's ratio of the material composing the cable. Moreover l_i is the actual length of the link, β_i and ψ_i are the bending and the torsional angles associated to the links.
From the energy terms the respective forces acting on mass-points can be computed: axial forces F_i^s, bending forces F_i^b and torsional forces F_i^t, such that:

$$\boldsymbol{F_i^s} = -\frac{\delta U^s}{\boldsymbol{\delta x_i}}, \quad \boldsymbol{F_i^b} = -\frac{\delta U^b}{\boldsymbol{\delta x_i}}, \quad \boldsymbol{F_i^t} = -\frac{\delta U^t}{\boldsymbol{\delta x_i}}$$

Internal forces are exploited in the optimization phase. The simulation phase works by solving the equations of motions iteratively, considering a discretization time $\Delta\tau$, providing the DLO behaviours under manipulation constraints.

4. Optimal trajectory planning for dual arm DLO manipulation

The planning strategy involves mainly two steps: the first phase is a model-based optimization, in which a path is provided for the considered DLO, to bring it from an initial shape to a final one. In particular a number S of intermediate shapes are computed. Since the DLO is represented through a number $n+1$ of mass-points, this problem is translated into finding an intermediate distribution of each mass-point composing the cable, from its position in the initial configuration, to the final one. The second phase aims to extract the gripper poses of the robot holding the cable associated to each intermediate shape at the two ends. Those gripper poses will be connected through linear motions in order to generate the trajectories for the dual-arm manipulation.

4.1. DLO-model-based optimization

This phase is divided in three steps. The path for the DLO is indeed provided by decoupling different aspects of the problem, in order to smooth the complexity in more optimization problems: the *basic geometrical optimization*, the *advanced geometrical optimization* and the *physical optimization*.

4.1.1 Basic geometrical optimization

This optimization step aims to find the shortest geometrical path for the DLO in order to bring it from the initial configuration ξ_o to the final one ξ_f. Such path is composed by S intermediate shapes ξ_i $(i = 1 \cdots S)$ discretized into $n+1$ mass-points, as shown in Figure 2.

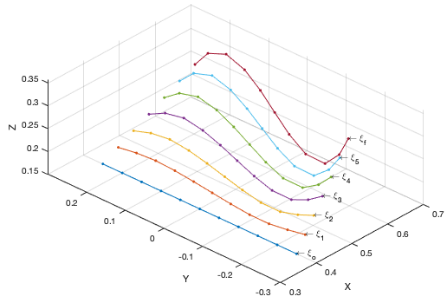


Figure 2: Basic geometrical planning.

The result can be considered the shortest path for the cable, being the shortest path for each mass-point composing the cable.
The coordinates of each mass-point composing an intermediate shape i are collected in a vector $\xi_i \in \mathbb{R}^{3(n+1)}$. Those vectors are the decision variables of the problem. The coordinate variation between adjacent shapes can be computed as vectors $\gamma_i = \xi_i - \xi_{i-1} \in \mathbb{R}^{3(n+1)}$, for $i = 1 \cdots S$, and they are used to provide distances between adjacent shapes. Note that $\gamma_f = \xi_f - \xi_S$.
This step aims to minimize those distances, providing a compact and smooth path for the cable. The problem is unconstrained, and the cost function is:

$$\min_{\xi_1,\xi_2,\cdots,\xi_S} \sum_{i=1}^{S} w_i||\gamma_i(\xi_i,\xi_{i-1})||^2 + w_f||\gamma_f(\xi_o,\xi_1,\cdots,\xi_f)||^2 \quad (2)$$

where w_i and w_f are the optimization weights.

4.1.2 Advanced geometrical optimization

This optimization step aims to prepare the intermediate shapes computed in the previous step, for the physical (energy) minimization.
In fact while the shortest geometrical path aims to provide a compact path for the cable involving geometrical deformations for the DLO, the

physical optimization step aims to search minimal energy configurations, avoiding huge deformations. However, during the *basic geometrical optimization*, the cable can be compressed, leading to large axial compression forces that may provide problems during the physical optimization. For this reason. this intermediate optimization step is implemented, in order to slightly modify cable shapes along the shortest geometrical path, stretching them, and avoiding compression of links.

The decision variables are the intermediate shapes mass-points coordinates ξ_i for $i = 1 \cdots S$. The cost is a multi-objective function composed by different terms:

$$\begin{aligned} \min_{\xi_1, \xi_2, \cdots, \xi_S} & \sum_{i=1}^{S} w_i ||\gamma_i(\xi_i, \xi_{i-1})||^2 \\ & + w_f ||\gamma_f(\xi_o, \xi_1, \cdots, \xi_f)||^2 \\ & + \sum_{i=1}^{S} w_\delta ||\delta_i(\xi_i)||^2 \\ + w_{clip} & \frac{1}{\Delta_{clip,i}} + w_\beta ||\beta_i(\xi_i) - \beta_{o,i}||^2 \end{aligned} \tag{3}$$

The first and the second terms aim to replicate the search for the shortest geometrical path carried out in the *basic geometrical optimization*. The third and the fourth terms are complementary: the third term aims to contain and minimize the enlargement of the length of the single links composing the shapes $\delta_i \in \mathbb{R}^n$, for $i = 1 \cdots S$, in order to counter balance the stretching of the whole cable provided by the fourth term, that maximizes the distance between the two robotic grippers holding the cable at the two ends $\Delta_{clips,i}$. The last term aims to impose a smooth curvature to cable shapes, imposing the curvature provided by the *basic geometrical optimization*, resumed in the bending angles $\beta_{i,o}$ associated to the shape, and hence the term $|\beta_{o,i} - \beta_i(\xi_i)|$ is used, where $\beta_i(\xi_i)$ are the bending angles related to the new shapes for $i = 1 \cdots S$. For this reason the computation of the *basic geometrical optimization* is not fully replaced by the *advanced geometrical optimization*, but must be performed for a smooth curvature extraction. w_i, w_f, w_σ, w_{clip} and w_β are the optimization weigths.

4.1.3 Physical optimization

This last optimization step aims to process each intermediate shape, in order to minimize the forces associated to the geometrical configurations provided by the previous optimization steps. Each shape is processed independently, distributing the problem complexity in more iterative steps. The decision variables are the mass-points coordinates of the intended shape $\xi_i \in \mathbb{R}^{3(n+1)}$ and the cost function is:

$$\min_{\xi_{min}} = w_\sigma ||\sigma||^2 + w_b ||F_b||^2 + w_s ||F_s||^2 \tag{4}$$

where σ is the variation from the geometrical proposed shape, and w_σ, w_b and w_s are the optimization weights. The problem is unconstrained, and the forces are extracted from the mass-spring model. Emphasis has been placed on the bending F_b and axial F_s forces, that can be considered the most relevant ones. Moreover the grippers orientations are not considered yet, and hence torsional behaviours can't be inspected in this phase. However, torsional effects will be minimized during the gripper computation phase.

4.2. TCPs trajectories definition

After the model-based optimization, the information provided through the planned shapes can be exploited in order to plan the intermediate poses of the grippers holding the cable. The positions of the grippers are defined as the intermediate points of the first and last link of each shape. The orientations of the grippers can be defined in many ways, some algorithms have been developed, involving an identification of the minimal rotation between adjacent shapes, or involving a rigid-approximation of the cable when dealing with stiff and curved DLO. Those methods aim to avoid the introduction of torsional behaviours in the cable during the manipulation.

5. Iterative planning through simulation

The planning step described in Section 4 provides the path for the end-effectors TCPs (tool center points) of a dual arm robot to bring a DLO from an initial configuration to a desired one. An additional phase involving simulation of the cable behaviour under manipulation constraints is implemented for two reasons: (1) to provide a static simulation of each intermediate shape in order to let the cable stabilize under gravity effects while held by the associated planned grippers; (2) to perform collision detection with modeled obstacles in the environment. A collision avoidance and a re-planning strategy through optimization are then implemented (Figure 3, 4).

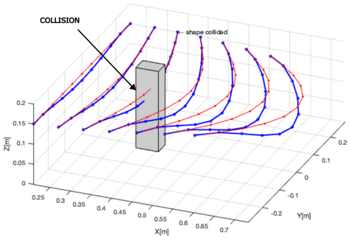


Figure 3: Collision detection.

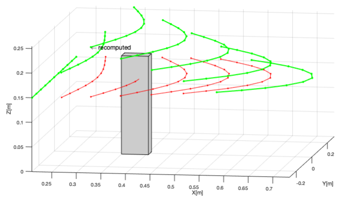


Figure 4: Obstacle avoidance.

6. Stiffness identification

In industrial frameworks different kinds of DLO are involved, with a wide variety of properties. Particular attention must be paid to the stiffness related to a DLO, because huge behaviours variations can be experienced. Such information can be resumed in the Young's modulus (E) associated to the DLO. Since many kinds of industrial cables are made of composite materials, and their Young's modulus can't be tabulated, an identification algorithm for the equivalent Young's modulus is developed.

6.1. Young's modulus identification

The strategy consists in performing a dual arm manipulation of a cable in the real world and in the simulation environment. Such manipulation must be informative, providing a bent final configuration for the cable. A least square algorithm is exploited in order to find the right value of E, comparing the simulated final shape with the real one (Figure 5).

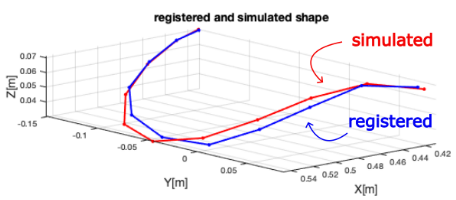


Figure 5: E identification for an USB cable.

6.2. Data-driven optimization tuning

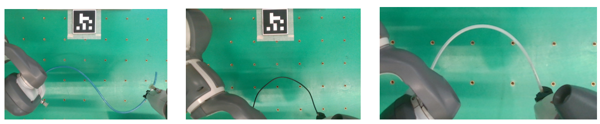
The obtained E is used in the optimization phase, in order to tune accordingly the weighting parameters for the cost functions, since variation of the stiffness leads to a variation in the relationship between geometrical deformations and generated forces, that can unbalance the optimization problem. The identified value of E is provided also to the simulation environment.

7. Experimental analysis and use case

A series of experiments and test, involving DLOs of different materials, were carried out. A quantitative analysis is provided for some two-dimensional manipulations, instead a qualitative analysis is provided for more complex manipulations. Moreover a use-case application involving a wire harness assembly operation for 3 different DLOs with different mechanicle properties is performed, exploiting the proposed method. The experimental setup is performed through an ABB Yumi Robot, and a RealSense camera is used for shape registration.

7.1. Quantitative analysis

For this part of analysis 3 tests are carried out: a "sinusoidal deformation" manipulation (M1) for a PU hose, and an "uniform curvature deformation" (M2) for an USB cable and a PA12 hose. The final shapes experienced during the tests are provided in Figure 6.



(a) M1(PU) (b) M2(USB) (c) M2(PA12)

Figure 6: Final shapes experienced during the tests.

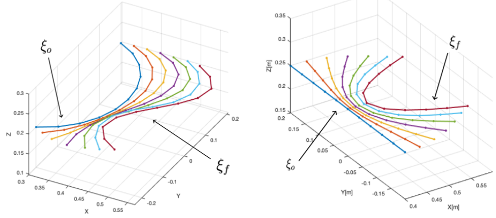
Each experienced intermediate shape is registered and discretized into $n+1$ points, in order to be compared with the planned ones. For the USB cable the Young's modulus was estimated.

	E [Pa]	error_{tot} [m]
M1	$1 \cdot 10^8$	0.0173
M2(USB)	$2.5 \cdot 10^6$	0.005
M2(PA12)	$1 \cdot 10^9$	0.0066

Table 1: Quantitative analysis results.

In Table 1 the averaged errors for the shapes experienced in the real manipulation are provided.

In Figure 7 the planned shapes are shown.

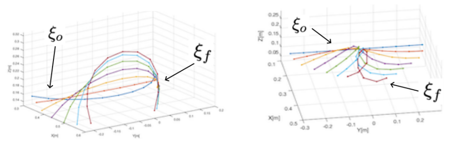


(a) M1 (b) M2

Figure 7: Planned and shapes for the quantitative tests.

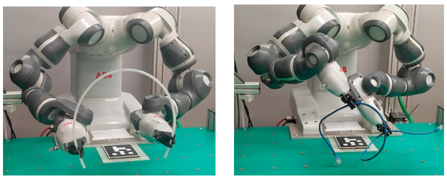
7.2. Qualitative analysis

For this part of analysis two manipulations are carried out: the planned shapes are provided in Figure 8, the final shapes experienced are shown in Figure 9. The expected behaviours are achieved during the manipulations.



(a) test-1 (b) test-2

Figure 8: Planned shapes for qualitative analysis.

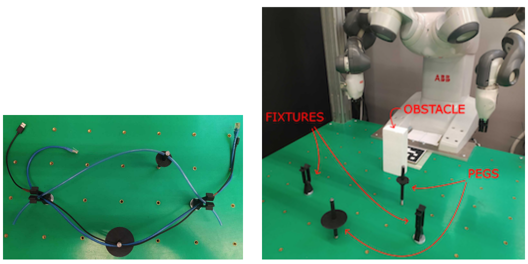


(a) test-1 (b) test-2

Figure 9: Obtained shapes for qualitative analysis.

7.3. Use case

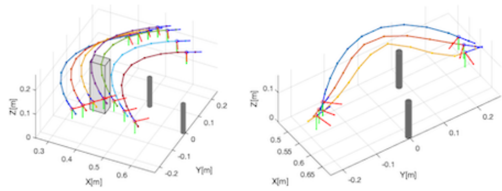
The use case examined in this work takes place in a wire harness assembly operation (Figure 10). A USB cable, an Ethernet cable and a PU-hose must be clipped in some fixtures and assembled through some pegs.



(a) Achieved operation (b) Framework

Figure 10: Use case operation.

Various kinds of stiffness are related to the different DLOs. The proposed methodology aims to plan the manipulation of the cables from their initial configurations to the final ones, providing the necessary curvature to the DLOs and performing obstacle avoidance. A second planning phase is carried out in order to align the cable ends with the fixtures, to prepare the cable for the insertion operation, as shown in Figure 11. The cable is then clipped into the fixtures.



(a) phase-1 (b) phase-2

Figure 11: Planning for PU-hose operation.

Some results about single operations are provided in Table 2.

DLO	E [Pa]	time[s]	success rate
USB	$2.5 \cdot 10^6$	9	86%
Ethernet	$7.5 \cdot 10^6$	9	93%
PU hose	$1 \cdot 10^8$	9	80%

Table 2: Single operations results.

The equivalent Young's modulus for the USB and the Ethernet cable have been identified before the manipulations. The expected behaviours are experienced during the dual-arm operation, and good success rates are achieved for each manipulation. Some issues can arise, related to non-modeled plastic deformations of DLOs, and contacts with fixtures during the clipping operation.

8. Conclusion

The proposed method aims to realize an offline model-based planning for a dual-arm robotic manipulation of a deformable linear object.
Low errors and good behaviours are achieved during the experimental phase, achieving the goal of performing an implicit planning involving deformable linear objects, even in a complex and industrial framework. Those behaviours are not affected by the material composing the cables, since the adaptation mechanism and the equivalent Young's modulus identification allows to properly manipulate various kinds of DLOs.
The methodology can be improved by building an online control scheme for the shaping of the cable, exploiting a visual servoing strategy.

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