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Robotic Wires Manipulation for Switchgear Cabling and Wiring Harness Manufacturing

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***Abstract*—This paper describes a cyber-physical system for a wiring operations, composed by a robotic manipulator and a gripper with tactile sensors. This system can be used for switchgear cabling and manufacturing of wiring harnesses. The manipulation of electrical wires, and more in general deformable linear objects, is a complex task of large interest for different industrial applications. The proposed system is designed to shape a cable along a desired path including fixing points and obstacles exploited to shape the cable itself. To accomplish this goal, the wire position needs to be determined starting from a list of point and then converted in a joint reference pose for the manipulator to reproduce the desired trajectory. Moreover, the wire tension must be controlled on the basis of both the estimation of the robot external wrench and the tactile data by acting on the gripper finger opening. An experimental setup in which a cable must be routed along two linear paths connected by a turn and with four fixing points has been used to validate the proposed solution.**

***Index Terms*—Robotic Manipulation, Deformable Objects, Cyber-Physical System, Industrial Manufacturing.**

I. INTRODUCTION

Due to his relevance in several industrial manufacturing applications, the manipulation of wires and cables, usually named as Deformable Linear Objects (DLOs), has been subject of various studies aimed to enable their manipulation and by an automatic platform just as a robot. In literature, the behaviour of DLOs has been largely studied, e.g. through the application of a FEM approach [1] or with a topological model based on knot theory [2] to solve knotting problems [3], or dealing with the DLO-in-hole problem [4]–[6]. Other models were designed in order to manipulate the wires to assume a certain shape [7] or to form knots [8]. In the field of industrial manufacturing, some studies can be found related to the assembling of electrical harnesses [9], [10] in which the idea of using environmental contacts to shape the wire along a desired path or to place it in a certain position is exploited. Another relevant problem in this field is the DLOs detection. Computer vision can be exploited before executing the grasp [11], but after grasping tactile sensors are usually the only way due to the occlusion provided by the gripping device itself [12].

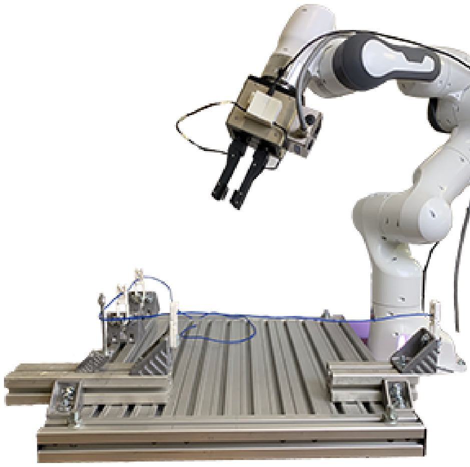

Fig. 1. The cyber-pysical system for cable manipulation composed by a robotic arm, a parallel industrial gripper and a pair of tactile sensors.

This paper focuses on the DLOs routing problem by analyzing the generation of feasible trajectories according to the expected path, described by a set of noticeable points and related semantic description, and considering the environmental constrains and obstacles, including relevant points that must be eventually exploited to fix the DLO in some position by means of clamps or clamps, e.g. emulating the manufacturing of a switchgear or a wiring harness. During this task, the robot must ensure a proper tension of the cable: a low tension may cause the cable to not follow the desired path or to not be fixed correctly, while an excessive tension may damage the cable and the related connections. Moreover, this preliminary study investigates how it is possible to control a DLO to remain in between the fingers during the routing with the fingers aligned in the vertical direction, preventing the cable to slip out of the finger because of the effect of gravity. Examples of related works focus on the contour following of the zip of a plastic bag [13], or on the manipulation of an USB charging cable where the position of the gripper is horizontal [14]. The problem is faced by designing a Cyber-Physical System (CPS), which physical parts can be seen in Fig. 1, composed by a robotic arm equipped with a Schunk PG70 industrial gripper which fingers include tactile sensors, enabling the robot to perceive the presence and shape of a grasped cable. Moreover,

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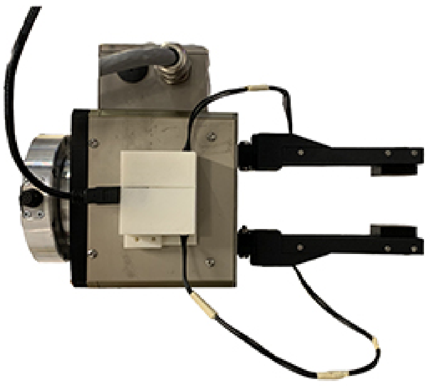


Fig. 2. The Schunk PG70 industrial gripper equipped with the tactile sensors.

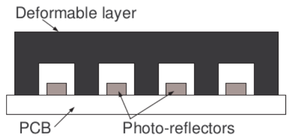


Fig. 3. Tactile sensor cross section view, in each chamber a photo-reflectors diode is capable of sensing if the chamber is changing.

the tactile data can be exploited to regulate the DLO tension and detect its interaction with the environment. Ultimately, a planner is designed to take as input the list of points over which the cable must pass and their semantic description, and then compute the trajectory for the robot that fulfill the expected DLO desired configuration and assembly sequence.

II. CPS DESCRIPTION

The CPS proposed in this work is shown in Fig. 1. It is composed by a robotic arm, a 7-DoFs Panda from Franka Emika, equipped with a Schunk PG70 industrial gripper which fingers include tactile sensors [15], [16], see Fig. 2. An overview of the most used technologies is available on [17]. The tactile sensors are composed by a PCB layers in which a grid of photo-reflectors devices are placed, see Fig. 3. These components produce a different of voltages whenever the light condition change. The sensors are enclosed in a chamber made of silicon forming a taxel and, by the combination of multiple taxels, it is possible to obtain sensors of different dimensions and size. The sensor used are composed by a 5×5 grid of taxels.

The software framework is based on ROS, while for the motion planning is been used MoveIt! which incorporate several motion planning algorithm from the Open Motion Planning Library.

To emulate a portion of a switchgear or of a wiring harness assembly jig, a track composed by aluminium profiles is used. The track defines a path with a 90° turn which is generally the turn expected to have in a switchgears. However, the solution may work also for application that involves different angles for example the production of the electrical harness of a vehicle. To hold the wire in position, some clamps are arranged along the path in which the cables must be fixed. The robot's trajectory must be designed so that it will be able to complete all the required actions aimed to fix the cable inside the clamps. Therefore, the planned trajectory needs to be analysed in order to verify that the robot keep the orientation of the end-effector fixed along the wiring direction in order to avoid the formation of knots in the wires.

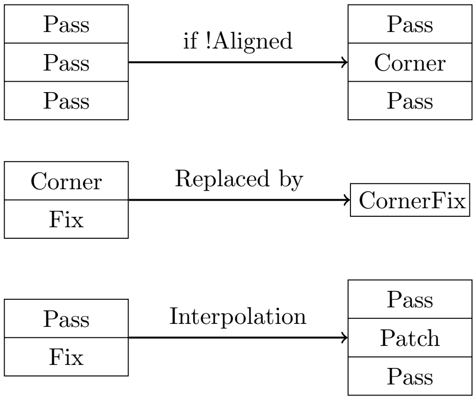


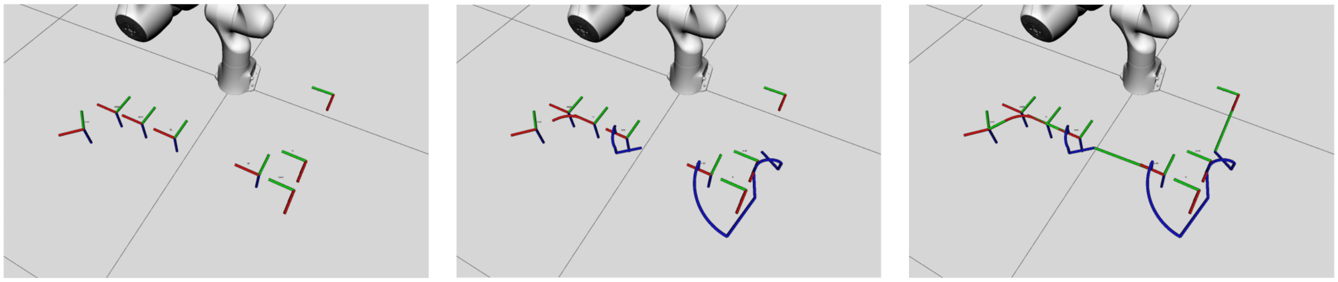
Fig. 4. Schematic processing of the trajectory points.

III. TRAJECTORY PLANNING

During the workspace trajectories generation, it is important to take into account the constraints in terms of cable tension and fixation requirements, together with the presence of obstacles along the path. Once the path in the workspace is obtained, it can be converted in a joint space trajectory by exploiting the robot inverse kinematics.

A. Path Generation

The final planning algorithm receives as input a list of point's coordinates expressed as a position and orientation in space plus the semantic description denominated as ”labels”, see Fig. 4. A label is a string that informs the planner the type of point, and therefore can be used by the planner to define the sequence of operations that must be executes in the specific point. This list of points is generated automatically from a database containing all the list of operation the robot must perform (insertion point, fixing point, cable routing and other) to complete the manufacturing of a certain product. As reported in Fig. 4, the first step performed by the planner is an analysis of the sequence of labels in order to detect specific patterns that are then replaced by a new set of semantic operations the robot must perform. Once the new label vector is obtained, the algorithm places the location of points in the workspace, as show in Fig. 5(a), then generates a vector of trajectories denominated ”Secondary Trajectories”, see Fig. 5(b), which are passed to the kinematic inversion algorithm to plan the final robot motion. The robot path planning is completed with the post-processing of the generated trajectory segments, in which the trajectories are interpolated in order to obtain a contiguous



(a) Point Generation.

(b) Secondary Trajectories.

(c) Trajectory Interpolation.

Fig. 5. The trajectory generation through different steps: a) point generation in the workspace; b) generation of secondary trajectories, Fix/Cornerfix Trajectories are shown in Red, Corners in Blue; c) interpolated trajectories in Green.

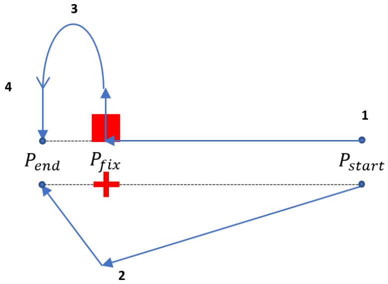


Fig. 6. Lateral and top view of a "Fix" Trajectory. To insert a cable inside the clamp, the robot first laterally approach the clamp (2), then perform a circular movement (3) to tension the wire and insert it inside the clamp (4)

list of equally spaced points at a given input distance, as shown in Fig. 5(c).

B. Secondary Trajectories

1) Fix Trajectory: The Fix Trajectory is characterized by the presence of a clamp along the expected path of the wires. This clam is used to hold and collect the wires in position after they are successfully placed. The clamp are placed with the insertion area facing up, a chamfer helps the wire to slide inside the clamp even in case of small misalignment error. The robot movement to insert the cable in the clamp can be divided in three parts, as shown in Fig. 6. From P_{start} (1) the robot moves laterally with respect to the clamp position P_{fix} (2) preserving the cable tension. Then, the gripper performs a combination of two movements (3), a semi-circular movement to place the wire over the clamp and a forward movement to align the cable in front of the clamp. With this combination of motions, the cable can be brought over the clamp while keeping the desired tension, in fact while the cable is at the centre of the semi-circumference, it reach his maximum elongation which is higher than the distance between the starting point and the clamp. To conclude the fixing task, the gripper is lowered, and the cable is inserted inside the clamp in P_{end}. It can be highlighted that a loose cable doesn't ensure a correct insertion: in that condition the wire settle over the clamp without having sufficient force to open it. However, in case the wire is pulled immediately after the missed insertion, the generated tension forces the wire to insert into the clamp.

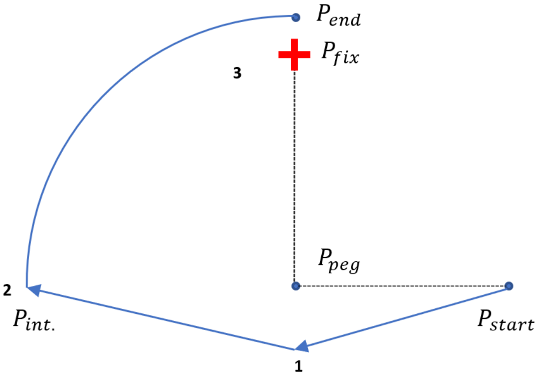
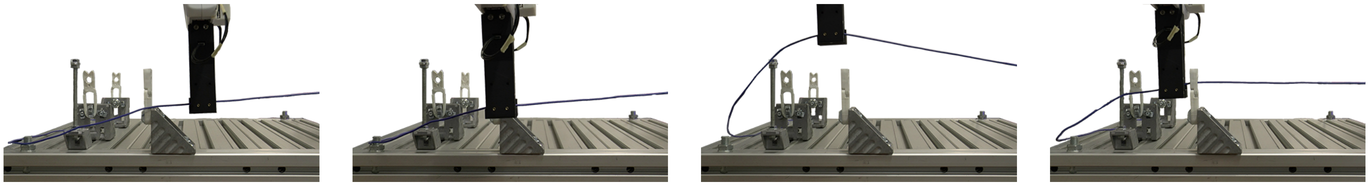


Fig. 7. Top view of the cornerfix trajectory. The wire is elongated avoiding the peg placed in the corner (1), once it has reached the desired length (2) is rotated around the peg moved over the clamp (3) to be inserted.

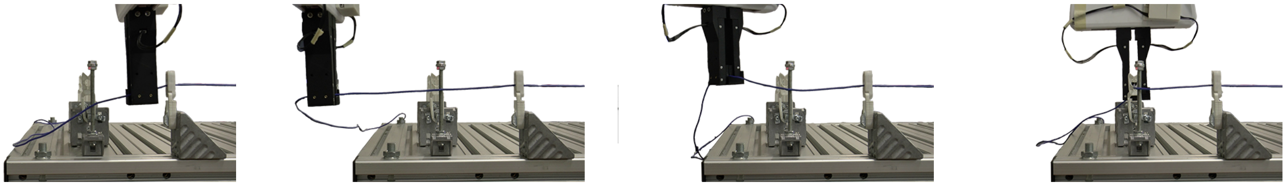
2) CornerFix Trajectory: An alternative version of the movement to insert the cables inside the clamp is denominated as "Corner-Fix" and is been specifically designed for the situation in which the robot must face a clamp right after a corner. In this case, a environmental constrain is exploited to change the cable direction and to keep the cable aligned with the desired path, which otherwise will be compromise by the deformation of the cable itself. With reference to Fig. 7, from the starting point of this trajectory P_{start}, an elongation phase is carried out in which the robot moves forward avoiding the obstacle positioned in P_{peg} (1) and then proceeds to an intermediate point $P_{\text{int.}}$ spaced at a distance equal to the sum of the length $\overline{P_{\text{start}}P_{\text{peg}}}$ and $\overline{P_{\text{peg}}P_{\text{end}}}$. This motion prepares the cable to the second movement, in which the gripper is rotates (3) around the corner point P_{peg} maintaining the cable tension. During the rotation the wire is also raised to move it on top of the clamp. The gripper orientation changes as well, to keep the fingers always aligned to the corner point. Once the rotation is completed, the gripper is lowers to insert the cable inside the clamp. The actual ending point P_{end} is ahead of the actual clamp position P_{fix} to avoid collision between the gripper and the clamp.

3) Corner rounding: The corner rounding is used whenever a change in the cable direction is needed, but no fixation is required as in the previous CornerFix Trajectory. It is also



(a) Clamp Approach. (b) Side Alignment. (c) Clamp Stepover. (d) Cable Fixing.

Fig. 8. Analysis of the sequence of action designed to fix a cable inside a clamp, during the movement the wire is first side-aligned with the clamp (b), then is moved over the clamp (c) and lastly inserted into the clamp (d). The cable is always kept in tension.



(a) Corner Approach. (b) Wire Sliding. (c) Gripper Rotation. (d) Cable Fixing.

Fig. 9. Experimental evaluation of the CornerFix sequence: From the starting point (a) the wire is pulled avoiding the peg (b). The cable is rotated and brought over the clamp (c). At the end, the gripper is lowered and the cable inserted in the clamp (d). The contact point is used to keep the wire in tension and with the correct shape.

supposed that an environmental constrain will be present in the internal side of the curve to preserve the position of the cable. The detection of the corners rounding is accomplished by checking if three points are not aligned. By looking at the sum of the points distance and if eq. (1) is not satisfied, the algorithm proceed with the generation and the insertion of a trajectory representing a smoother round.

$$\overline{P_1P_2}+\overline{P_2P_3}-\overline{P_1P_3}<\epsilon \tag{1}$$

Where ϵ is a suitable threshold. The curvature is obtained by using a quadratic Bezier curve, that given three control points as input, allows to compute a smooth turn by the quadratic interpolation the provided points in space. By varying the free parameter $s \in [0,1]$ is possible to generate the required subsequently of points through the following relation:

$$p(s)=P_2+(1-s)^2(P_1-P_2)+s^2(P_3-P2) \tag{2}$$

The orientation of the points are changed as well, to modified the orientation is used the Spherical Linear Interpolation [SLERP] that linearly interpolate the orientation of the gripper.

$$q(s)=[q(P_1)+q^{-1}(P_3)]^s q(P_1) \tag{3}$$

Where $q(P_i)$ represents the unit quaternion orientation of the generic point P_i.

C. Trajectory interpolation

The trajectory computation is completed by performing the interpolation of the path connecting the secondary trajectories provided a certain maximum distance between two point is defined. If the actual distance among two points, let's call them P_{start} and P_{end} respectively, is higher than the desired one, a linear interpolating among them is generated by varying the parameter $s \in [0,1]$, while the SLERP algorithm is exploited to perform a smooth rotation.

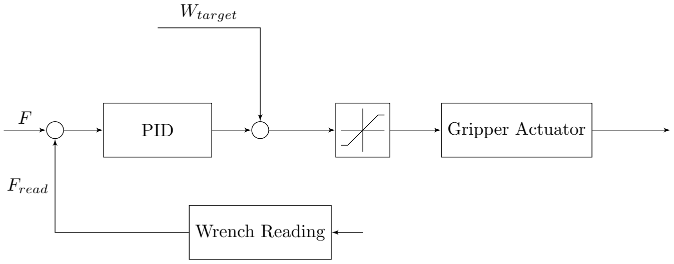


Fig. 10. Control scheme used to adjust the cable tension during the routing.

$$p(s)=P_{\text{start}}+s(P_{\text{end}}-P_{\text{start}}) \tag{4}$$

$$q(s)=[q(P_{\text{start}})+q^{-1}(P_{\text{end}})]^s q(P_{\text{start}}) \tag{5}$$

IV. CABLE TENSION AND CENTERING CONTROLLER

A. Gripper Tension Controller

A loose cable may not follow the desired path or can not be fixed in the clamps, while too much tension may damage the cable and the product. Therefore, the objective of the cable tension control is to guarantee the correct execution of the routing task. In fact, the tension control, which schematic is represented in Fig. 10, is implemented by a PID controller that acts on the distance between the two gripper's fingers, in order to impose a certain tension to the cable: if the tension force increases, this means that the gripper fingers are too closed the wire cannot slide properly, and the robot needs to increase the pulling force. Since the robot is capable to apply a high force through to the cable, the control requests to wider the gripper's finger in order to permit the cable to slide

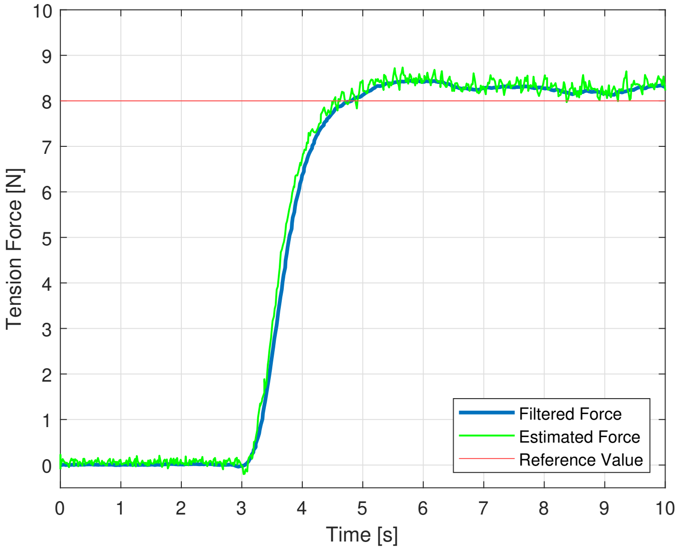


Fig. 11. Control of the wire tension: force reference (red), estimated force (green) and filtered estimation (blue).

easily to avoid the damage the of structure of the switchgear or the connectors. On the contrary, if the force is lower than the reference value, the gripper closes the fingers to apply a higher tension thus avoiding to have a loose cable placement. The designed control loop works at a frequency of 50Hz and takes as input the estimation of the tension force, which details are provided in the Sec. IV-B, in the sliding direction of the cable. The output of the regulator is saturated to limit the requested width of the gripper opening, in order to avoid to open the gripper excessively so that the cable can fall, or at the contrary prevent to damage the fingers if a tight close is requested. The value W_{Target} represents an estimation of the gripper opening selected on the basis of the diameter of the cable to be manipulated, and it is adopted as feedforward input to improve the controller performance.

B. Wrench Data Estimation

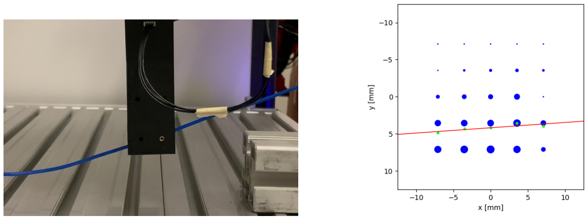
First, the acquisition of the external wrench that is required to use this information as input in the controller. The external force is estimated starting from the reading of the joints torques provided by the robot low-level controller. The acquired data are then converted in the external wrench data vector based on the Euler-Lagrange model of the robotic manipulator

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + D\dot{q} + g(q) = \tau + J^T(q)F \tag{6}$$

This relationship can be inverted to isolate the external wrench

$$F = J^{\#}(q)[M(q)\ddot{q} + C(q,\dot{q})\dot{q} + D\dot{q} + g(q) - \tau] \tag{7}$$

where $J^{\#}(q)$ is the pseudoinverse of the Jacobian transpose since the Jacobian is a $7{\times}6$ matrix, therefore the inverse cannot be calculated, then his pseudo-inverse can be used instead. To efficiently compute the pseudoinverse of $J^{\#}(q)$, the Singular Value Decomposition [SVD] method is applied. The robot internal contorller requires the torque data to be published at a frequency of 1000Hz. Therefore, in this frequency range the wrench estimation is sensible to external disturbances such as the vibration of the mounting base of the robot. It follows that, in order to have a more robust input signal for the controller, the data need to be filtered using a Moving Average filter, as shown in Fig. 11 where the force input reference provided to the controller is reported in red, the estimated force is in green and the filtered estimation used as feedback in the control loop is shown in blue. Then, the control output is published at the lower frequency of the gripper controller.



(a) The cable grasped in non-centered position.

(b) Corresponding Tactile map.

Fig. 12. The tactile sensors enables to estimate the position and the orientation of the cable by means of a first order curve estimation.

C. Vertical Trajectory Correction

A correction of the vertical trajectory during the cable sliding is implemented to guarantee the correct alignment and centering of the cable with respect to the tactile sensors. Despite the alignment of a cable with a tactile sensors has been already proposed in [14], in this case the scenario is much more complicated since the fingers need to be placed vertically to fit inside the switchgear's cable collectors, thus gravity applies a constant disturbance that tends to pull the cable out from the gripper. As shown in Fig. Fig. 12, the controller exploits the the voltage's readings provided the tactile sensor mounted in the gripper to detect the wire's position and orientation with respect to the sensor. The tactile sensor data are used to fit a first order function.

$$y = mx + n \tag{8}$$

Where n represents the distance of the cable from the centre of the sensor and m its orientation. Therefore, the trajectory correction modifies the vertical position of the gripper during the cable sliding in order to minimize the value of n, i.e. try to maintain its value close to zero, in order to center the cable with respect to the sensor and then preventing the cable to fall out from the gripper.

V. EXPERIMENTAL EVALUATION

The experimental evaluation of the CPS described in Sec. II is reported in this section. The test bench is composed by two linear traits connect by a 90° corner, the distance between the starting point and the first clamps is 46 cm, which consists in the longest distance between two duct that can be found in the reference switchgear adopted along the project. A typical execution sequence is reported in Figures 8 and 9. In particular, Fig. 8 reports a detailed view of the sequence of motions designed to fix a cable inside a clamp: during the clamp approach phase, see Fig. 8(a), the cable is first side-aligned with the clamp as shown in Fig. 8(b), then the cable is moved over the clamp in Fig. 8(c) and lastly inserted into the clamp in Fig. 8(d). Note that the cable is always kept in tension during the task. In Fig. 9 the experimental evaluation of the CornerFix sequence is reported: From the starting point shown in Fig. 9(a) the wire is pulled avoiding the peg, see Fig. 9(b). The cable then is rotated and brought over the clamp in fig. 9(c) and finally the gripper is lowered and the cable inserted in the clamp, as reported in Fig. 9(d). Note that the corner point is exploited to keep the wire in tension and shape according to the desired path. Several execution tests have been evaluated over the proposed test bench, from which we have evaluated that the proposed CPS is able to accomplish the cable routing task without with a success rate close to 100%.

VI. CONCLUSION

In this work, the feasibility of the execution of a cable's routing by a robotic manipulator is successfully proved. These preliminary results open the way to industrial applications like switchgear manufacturing or wiring harnesses assembling. The introduction of tactile sensors permits the perception of an object inside the gripper that otherwise will be unknown to the robot. Moreover, the sensor's information also add the possibility to monitor constantly the manipulation process, fact that is fundamental in case of deformable objects to develop various solutions for fault detection and diagnosis in real case scenarios. A trajectory planner able to process a semantic description of the path and generate from this description a feasible trajectory enabling the execution of the manufacturing task has been validated. The cable tension control implemented on the gripper allows to preserve the desired traction force on the cable along the manipulation process, so that it will avoid to have loose cables or causing damage to the components of the switchgear. An online correction of the trajectory is also proposed to maintain the cable correctly aligned with the fingers. Experimental validation is provided over a laboratory test bench, showing the capability of the proposed CPS to accomplish the desired task.

Future works will be devoted to evaluate the CPS on more complex and realistic scenarios, considering the constraints of a real manufacturing line and the planning of the whole sequence of operations required for the production of a finished product.

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