Wire Grasping by Using Proximity and Tactile Sensors

Andrea Cirillo, Gianluca Laudante, Salvatore Pirozzi
Dipartimento di Ingegneria, Università degli Studi della Campania "Luigi Vanvitelli" Via Roma, 29, Aversa (CE), Italy

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***Abstract*—Nowadays robots have to be able to perform increasingly complex tasks. In grasping and manipulation, the knowledge of the environment and the pose of the target object are crucial for the correct execution of the task. Vision systems are widely used for environment and object perception, but they need to be finely calibrated to obtain high accuracy and they are not able to sense small objects like thin wires. Tactile sensors could be used to explore areas close to the target object, but this "blind" physical interaction is not always feasible. This paper proposes a strategy to use a proximity sensor mounted on the robot's end effector to obtain a pose estimation of the target object that, in this study, is represented by a thin electrical wire.**

***Index Terms*—Wire Grasp, Proximity Sensors, Tactile Sensors**

I. Introduction

Robots are increasingly used to perform complex tasks in unstructured and dynamic environments and in collaboration with the humans. For the autonomous implementation of complex tasks in a human-like way, it is very useful to equip the robot with a multi-modal sensory system. In a lot of tasks, in order to properly manipulate the objects, robots have to be able to perceive them and to estimate their pose with high accuracy, before to start the grasping and/or the manipulation actions. These tasks are still challenging, since the accuracy of object features (e.g., shape, pose) estimation heavily depends on the type of perception systems used, as here discussed.

In particular, vision and depth cameras can be used to sense objects from relatively high distance, in order to obtain initial information about object to grasp. However, the object geometric information are estimated with low accuracy due to errors related to occlusions and calibration procedures. These known problems still represent a limitation even though the distance between the sensor and the object is reduced, as discussed in [1].

On the other side, tactile sensors are increasingly used for the manipulation tasks, as they allow complex control actions when the robot is in strict contact with an object [2], [3]. The starting point for grasping and manipulation should be the object pose estimated by the cameras. If it is estimated with a low accuracy the grasping may fail and the whole task may be infeasible. Tactile sensors are typically installed on the robot end-effector (e.g., robot grippers, robotic hands) and they could potentially be exploited to perform exploration phases in areas closer to the objects that could be not accessible to cameras. In this way the tactile sensor could be used to improve the accuracy of the environment knowledge before the execution of grasping/manipulation tasks.

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The main idea proposed in this paper concerns the installation of proximity sensors on the end-effectors, by enabling robots to rely on pre-touch sensing, in order to increase the accuracy of the object pose and shape estimation during the approaching and grasping. Differently from tactile sensors and vision systems, proximity sensors work at an intermediate range, providing benefits to both the mentioned class of sensors: integrated to the robot end-effector, they are more robust with respect to occlusions; they may potentially provide more precise measurements in closer range; they do not require to get in contact with objects. From a practical point of view, their use can be integrated with the other cited sensors. For example, through specific scanning strategies defined on the basis of camera data, proximity sensors would enable robots to acquire additional, more accurate geometric information of an object, in order to perform grasping actions, manipulation and re-grasping also in combination with tactile data. Pre-touch sensors based on different technologies have been already used in robotics during last years.

Electric field pre-touch sensors have been widely used [4]–[6], by exploiting electric field to reconstruct the irradiated object features: their use is limited to conductive materials. Acoustic pre-touch sensors have been proposed in [7], [8], where the seashell effect has been exploited. Optical sensors appear the most promising since they can be used with a wide range of materials. In [9]–[11], authors exploited the amount of light reflected by the objects to reconstruct with high precision the shape or the distance of the object of interest. These approaches present intrinsic problems related to colour and surface reflectivity. Optical proximity sensors based on Time-of-Flight (ToF) technology represent a solution to overcome some of the mentioned issues. ToF sensors do not need calibration and they are robust and accurate enough with a wide range of materials and in the execution of several different tasks [1], [12]–[14]. For the sake of completeness, the authors would remark that proximity sensors can provide relevant data also in safety critical situations, e.g., Human-Robot Collaboration tasks [15], [16].

Considering the good performance and the limited dimensions of the new off-the-shelf ToF sensors, the authors of this paper presented in [14] a new pre-touch sensing solution, fully integrated in the pre-existent tactile sensors developed by some of the authors in the last ten years [17], [18]. The main objective is the manipulation of Deformable Linear Objects (DLOs), e.g., thin electrical wires, within the activities of H2020 REMODEL project[1]. A precise knowledge of the wire pose obtained with proximity sensors in the pre-grasping phase can be used to correct the a priori knowledge on the grasping target obtained with cameras, in all the cases where vision data may be not sufficiently accurate, i.e., with small, thin and/or transparent objects [19]. The combination of 2D camera images in wire shape recognition, after a calibration procedure, can be sufficient only in specific constrained conditions [20], e.g., when the cables lie on a known flat surface (workbench plane). But in more general conditions, where the manipulation requires the estimation of the object 3D pose, an accurate 3D reconstruction in the Cartesian space by using 2D camera images is quite challenging and computationally expensive as shown in [21], for problems related to the alignment of the multiple views by considering the particular features of DLOs.

In this paper, the ToF sensors integrated with tactile sensors in the same robotic finger are used for the precise grasping of thin wires in different conditions: cable lying on the workbench and cable raised from the workbench. The proximity sensor can be used in both cases but in a different way: for this purposes a characterization of ToF sensors for close distance is presented and exploitation strategies are also proposed. The fingers have been equipped with suitably designed mechanical fingernails to lift the wires from the workbench surface. An optimized scanning strategy by exploiting wire properties to reduce scanning time is also proposed. In both working conditions, the tactile sensor can be used to evaluate the effectiveness of the proposed solution for wire grasping in a desired pose. Specific experiments have been carried out to evaluate the results.

II. The Sensorized Finger

A. The Hardware

The starting sensorized finger with integrated tactile sensor is the one detailed in [18]. It consists of a sensing pad with a matrix of 5×5 taxels based on optoelectronic technology. The sensor provides a tactile map constituted by 25 signals, corresponding to a distributed pressure map, with a spatial resolution of $3.55\,\text{mm}$. The signals are managed by an on-board Microchip PIC16F19176 microcontroller, and interfaced with the PC trough a standard serial bus. Details about tactile sensor characterization can be found in [18].

The proximity sensing system has been designed in order to be compatible with the existing tactile sensor solution. The mechanical case housing the proximity sensing has been designed in such a way it can be installed on the rear side of the finger sensorized with the tactile sensor. Figure 1 shows how the designed case is integrated with the finger. The mechanical design foresees the possibility to install proximity sensors all around the finger. From the electronic point of view, the proximity sensors are constituted by the VL6180X ToF devices, manufactured by STMicroelectronics, directly interfaced with the main Printed Circuit Board (PCB). The PCB board provides a compact ($24 \times 34\,\text{mm}$) interrogation system for the ToF sensors. The board can host up to 4 ToF sensor modules, managed via I2C interface by the microcontroller PIC16F19176, manufactured by Microchip, externally interfaced with the PC trough a standard serial bus. Figure 1 on left reports a picture where the main PCB and 3 ToF sensors are highlighted. Additional details both from hardware and software point of view can be found in [14].

[1] https://remodel-project.eu/

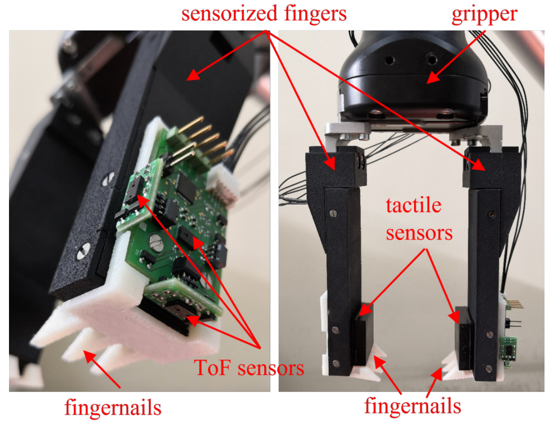


Fig. 1. Pictures of sensorized fingers with tactile and proximity sensors.

Since one of the objective of this work is the grasping of thin wires from the plane of a workbench, a mechanical adapter is necessary to allow the fingers to lift the wire from the plane and grasp it among the tactile sensors. To this aim, a sort of "fingernail" has been designed as part of the proximity sensor housing, allowing the complete closure of the parallel gripper fingers, during the lift of the wire. From Fig. 1 it is possible to see how the fingernails are constituted by teeth, suitably offset between the two fingers, in order to intersect themselves during a closure without touching each other. Additionally, the teeth present an inclination that allows the lift of the wire during the gripper closure. The described behaviour is well shown in Section IV and in particular in Fig. 6.

B. Proximity Sensor characterization

This section presents the results of some tests devoted to understand the behaviour of the proximity sensor when the target object is very close to the sensor. The datasheet of the VL6180X reports a minimum working distance of $10\,\text{mm}$, but it is interesting to see if the measurement obtained below this threshold can be somehow useful although incorrect.

In the first test, the proximity sensor approaches a target while continuously measuring the distance every $0.02\,\text{s}$ (i.e., at $50\,\text{Hz}$). The measurement given by the sensor is then compared with the actual distance of the target, obtained by knowing the relative position of the target object and the robot's end effector where the sensor is installed on. The distance varies in a range from 2 to $50\,\text{mm}$ and the experiment is repeated on targets with different reflectivities (i.e., white, grey and black targets). The results of the tests with the three considered

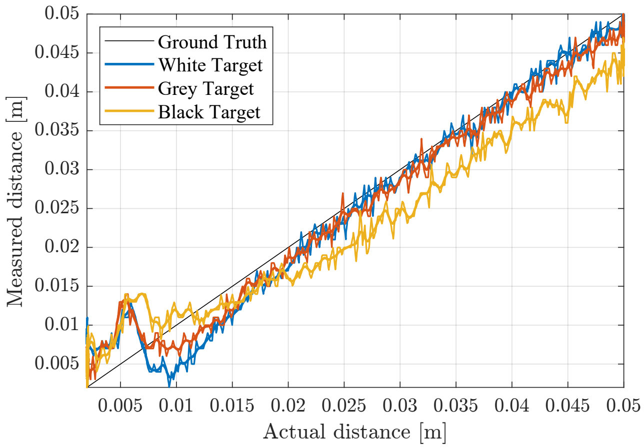
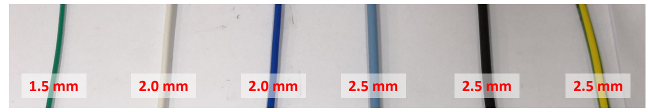
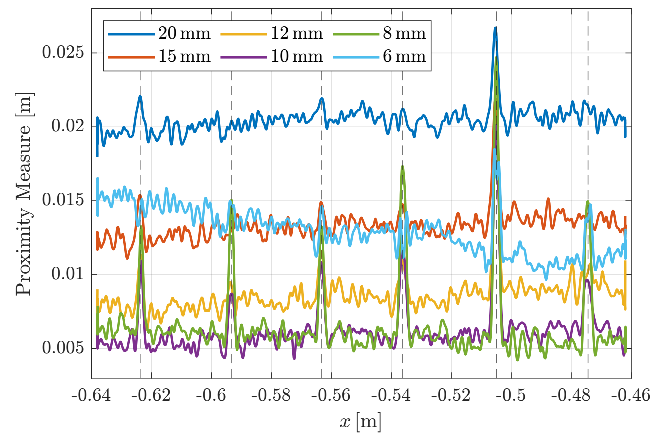


Fig. 2. Proximity measurements when approaching targets with different reflectivities.



(a)



(b)

Fig. 3. Wires used in the experiment (**a**) and results of the scanning at distances equal to 6, 8, 10, 12, 15, and 20 mm (**b**). Graphs show how at a suitable distance the wires can be detected by exploiting the "jump" of the proximity sensor characteristic.

targets are reported in Fig. 2. When the distance is greater than 15 mm, the sensor measurements (blue, red and yellow lines) grow linearly with the target distance, as it should be in the ideal case, with an error w.r.t. the ground truth (black line) which depends on the target reflectivity (lower error with higher reflectivity). Below the 15 mm threshold, instead, the measurement curves have a particular behaviour. The measured distance is lower than the ground truth in the range $[10, 15]$ mm and it suddenly becomes greater than the ground truth in the range $[5, 10]$ mm. In particular, there is a "jump" of 16.3 mm with the white target, 12.8 mm with the grey target and 6 mm with the black target.

Given the results of the experiment, it is clear that the sensor cannot be used as a proximity sensor with small targets' distances. Nevertheless, this behaviour could be exploited to detect wires on a flat surface: when the sensor is close enough to a surface, even a small negative variation in the distance between the sensor and the target (i.e., target closer to the sensor) causes a relatively big variation in the measurement. This is the case, for example, of a thin wire placed on the workbench. To confirm this intuition, a specific experiment is carried out in which some wires with different diameters and colors (see Fig. 3(a)) are placed on a workbench covered with a common white paper. White has been chosen since it has the lowest error at big distances and the highest "jump" at small distances. Similar results, but with lower sensitivity, can be obtained with the other targets. Then, the wires are scanned with the sensor places at different distances. The results are reported in Fig. 3(b) where the peaks in the proximity measurements correspond to the wires position. These peaks are consistent with the results of the previous experiment and from the graph it can be seen that the peak value also depends on the color of the wire. For instance, the last three peaks have different maximum values although all the corresponding wires have a diameter of 2.5 mm. This could probably depend on the different reflectivities of the wires or on the different contrast they have w.r.t. the background. From presented experiments, it is clear that the sensor response is independent enough from the background color and reflectivity for distances greater than 15 mm, while for closest distances it can be still used to detect wires, but having in mind that the measurement does not correspond to the real object distance.

III. The Scanning Strategy

This section presents a strategy to exploit the proximity sensor for the localization of a wire placed on a workbench. Such information can be then used to compute a suitable

Algorithm 1 Pseudo-code of the scanning strategy

procedure SCANNING(Δx, Δy, δ, s)
  $lineExtent \leftarrow \begin{bmatrix} x_{curr} & x_{curr} + \Delta x \end{bmatrix}$
  $numRows \leftarrow ceil(\Delta y / \delta)$
  $wirePoints \leftarrow$ empty array
  $startPoint \leftarrow$ current position
  for $row \leftarrow 0$ **to** $numRows$ **do**
    scan one line
    while not($wire\,detected$) **or not**($end\,of\,line$) **do**
      wait
      if ($wire\,detected$) **then**
        go on for s
        add new point to $wirePoints$
        compute $startPoint$ from $wirePoints$
      else if ($end\,of\,line$) **then**
        compute $startPoint$ from current position
      end if
      go to $startPoint$
    end while
  end for

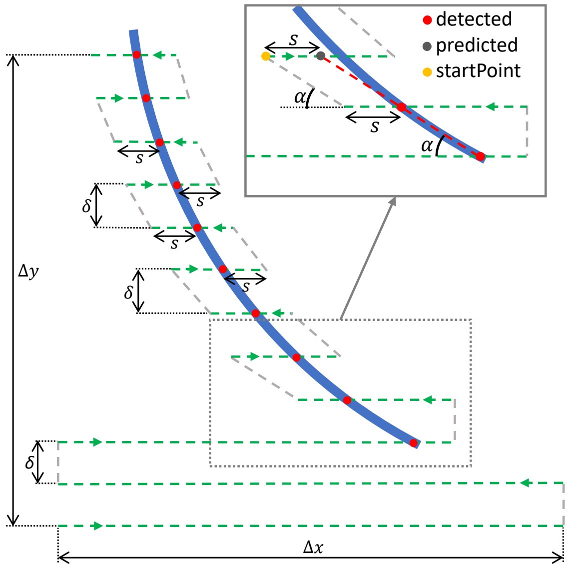


Fig. 4. Optimized scanning strategy

grasping pose for the robot's end effector. The scanning strategy is an optimized version of the one proposed in [14], where the trajectory is computed offline from user defined parameters and the corresponding area is scanned entirely.

The pseudo-code of the scanning strategy is reported in Algorithm 1. The input parameters are: Δx and Δy for the dimension of the area to scan with respect to the current pose of the robot's end effector, δ for the distance between two consecutive scanned lines (i.e., the green ones in Fig. 4) and s is the distance that the robot's end effector has to cover before to step to the next line once the wire is detected. The lower bound for the s parameter is the wire diameter, while the upper bound depends on the specific application, i.e., the more the wire is inclined w.r.t. the fingers, the greater the s value needs to be.

After some variables initialization, a for loop is executed until the number of the scanned lines is equal to $ceil(\Delta y/\delta)$. The first operation in the for loop is to command the robot to scan an entire line, then a while loop is used to wait for one of the following two events: the detection of the wire or the reaching of the end of the scanning line. In case the latter occurs, the robot simply goes to the next line, as it is shown in the first two lines at the bottom of Fig. 4. In the other case, first the robot is commanded to go on for a distance equal to s (see Fig. 4), then the new point is stored in a dedicated vector $wirePoints$ (red dots in Fig. 4) and the $startPoint$ of the next scanning line (yellow dot in Fig. 4) is computed considering the last two points in the vector. This last operation can be seen as a sort of one-step ahead prediction of where the wire should be in the next line, approximating the wire as a straight line passing through the last two detected points (see the grey rectangle in Fig. 4). The main difference between the strategy proposed in [14] and the one explained above is that in this optimized version, when the wire is detected, the scanning trajectory is updated online in order to scan only a small area nearby the wire. By using the original strategy, instead, the robot scans the whole area defined offline by Δx and Δy (see Fig. 4). As a consequence, the duration of the optimized scanning procedure is highly reduced.

The scanning strategy proposed in [14] was successfully exploited only in the case of a wire lifted from the workbench. In this case, instead, exploiting the behaviour of the proximity sensor shown in Sec.II-B, the same strategy can be used even when the wire is directly placed on the workbench. The only difference is that the measure given by the proximity sensor gives an information on the presence of the wire but not on its z-coordinate. Nevertheless, this is not a problem since the height of the wire corresponds to the one of the workbench, which is known.

IV. Grasping Experiments

This section shows two experiments regarding the scanning and the subsequent grasping of a wire in two different conditions: lifted from the workbench in the first one and directly placed on it in the second one. The hardware setup used for the experiments consists in an UR5e robotic arm from Universal Robots equipped with a Hand-E Adaptive Gripper from Robotiq. The fingers mounted on the gripper are two custom fingers with tactile sensors, proximity sensors and fingernails on the tip as explained in Sec. II-A.

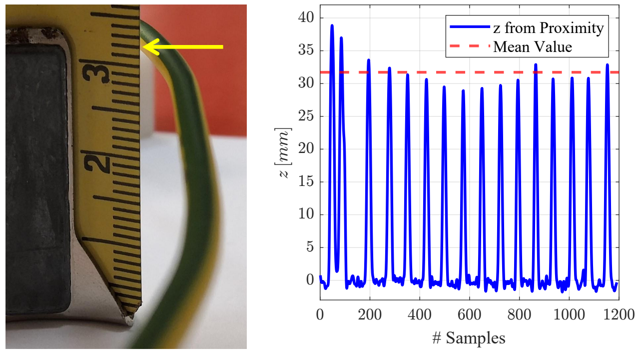
The input parameters of the scanning algorithm used for the experiments are: $\Delta x = 0.2\,\text{m}$, $\Delta y = 0.15\,\text{m}$, $\delta = 0.01\,\text{m}$ and $s = 0.01\,\text{m}$. The cruise velocity of the end effector during the scanning procedure is $0.02\,\text{m/s}$. Both the experiments make use of the same scanning strategy explained in the previous section to localize the wire and then compute a suitable pose for the end effector in order to correctly grasp the wire. In particular, the wire points detected during the scanning procedure are used to compute a second order polynomial approximating the wire and then this approximation is exploited to obtain the correct position and orientation of the end effector for the grasping phase. If the function approximating the wire is the following:

$$y = f(x) = ax^2 + bx + c \tag{1}$$

the homogeneous transformation matrix representing the pose of the end effector w.r.t. the base of the robot for the grasping task can be written as

$$\mathbf{T}_e^b(\hat{\mathbf{p}}) = \begin{bmatrix} \sin(\alpha) & -\cos(\alpha) & 0 & \hat{x} \\ -\cos(\alpha) & -\sin(\alpha) & 0 & \hat{y} \\ 0 & 0 & -1 & \hat{z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

with $\alpha = \tan^{-1}(f'(\hat{x}))$. With such grasping pose, the wire will be exactly placed in the middle of the two fingers and the line passing through the centers of the two tactile pads will be orthogonal to the tangent to the wire in the chosen grasping point, i.e. $\hat{\mathbf{p}} = (\hat{x}, \hat{y}, \hat{z})$. The latter, in the following two experiments, is the point of the approximated wire at a distance of 3 cm, in the sense of the curvilinear abscissa, from the first point detected during the scanning procedure.



(a) (b)

Fig. 5. Real height of the wire (**a**) and height computed from proximity sensor measurements (**b**).

In the experiment with the wire lifted from the workbench, the distance between the workbench and the proximity sensor during the scanning procedure is 45 mm and the speed of the end effector is 1 cm/s. In this case, the $\hat{z}$-coordinate in the matrix (2) can be directly obtained from the measurements of the proximity sensor, as it can be seen from Fig. 5. Figure 5(a) shows the real height of the wire, which is about 32 mm. Figure 5(b), instead, reports the height values measured during the scanning phase which is computed as

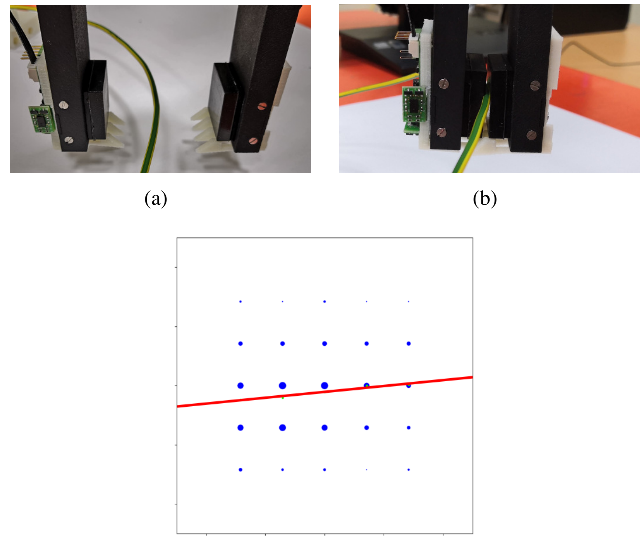
$$z_{target} = z_{prox} - d_{meas} \tag{3}$$

with z_{prox} being the height of the proximity sensor w.r.t. the workbench, obtained by using the direct cinematic of the robotic arm and d_{meas} the distance measurement given by the sensor. The peaks in the graph correspond to the moments when the sensor crosses the wire during the scanning and the mean value of these peaks is 31.8 mm. Moreover, in case the $\hat{z}$-coordinate was not precise enough, the tactile sensor could be exploited to apply a correction as shown in [3].

Figure 6 shows the grasping pose with the fingers aligned to the wire (6(a)), the position of the wire after the grasp (6(b)) and the respective tactile map with the estimated wire position read from the tactile sensors (6(c)). The algorithm used for the estimation of the wire position by using the tactile sensor is explained in [3].

Figure 7 shows the wire approximation resulting from the scanning procedure, where the red dots are the points detected from the proximity sensor and the blue line is the polynomial function used to approximate the wire. The number of detected points depends on the scanning parameters and it allows greater precision in the estimation of model parameters, by using a least squares method, and the possibility in future of estimating more complex, e.g. non-quadratic, shapes for wires.

Regarding the experiment with the wire placed on the workbench, the distance between the workbench and the proximity sensor is 10 mm with the same speed of the previous experiment, i.e., 1 cm/s, but in this case the height of the wire can not be retrieved by using the proximity sensor. The characterization in Sec. II-B shows that the measurement given by the sensor when the target is too close does not have a physical meaning. For this reason, the $\hat{z}$-coordinate in the transformation matrix (2) is fixed and it is obtained from the height of the workbench, supposed known. Figure 8 shows the result of the scanning procedure for this second experiment.



(a) (b)

(c)

Fig. 6. Fingers aligned for the grasp (**a**), wire at the center of the tactile pad (**b**) and tactile map with wire position estimation from the tactile sensor (**c**).

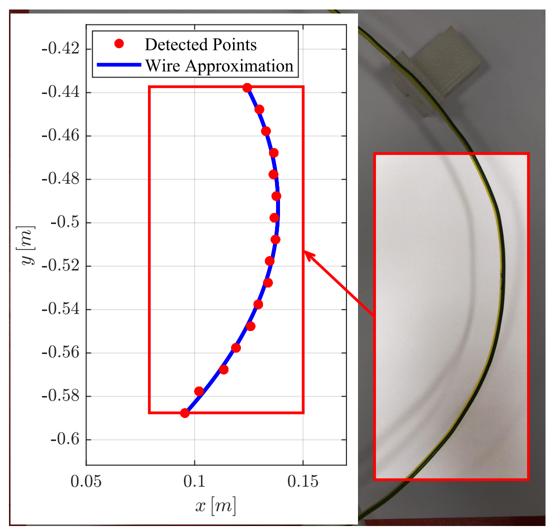


Fig. 7. Result of the scanning procedure with the lifted wire.

In Fig. 9(a), instead, it is possible to see the alignment between the wire and the fingers. Figure 9(b) shows the detail of the fingernails lifting the wire and Fig. 9(c) shows the fingers fully closed. Since the wire is in contact with the tactile pads, the signals coming from the tactile sensor, reported in Fig. 9(d), can be used to assure that the grasp was successful.

To quantify the optimization of the scanning strategy the scanning duration for the proposed experiments has been compared with the corresponding duration obtained by applying

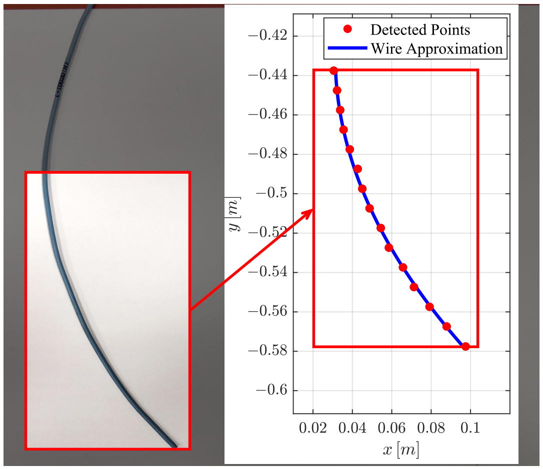
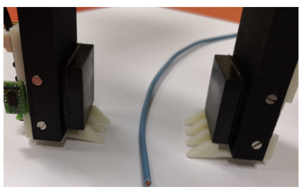
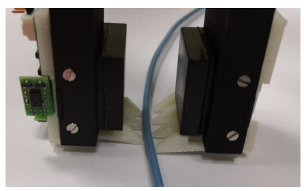


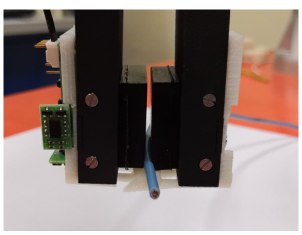
Fig. 8. Result of the scanning procedure with the wire placed on the workbench.



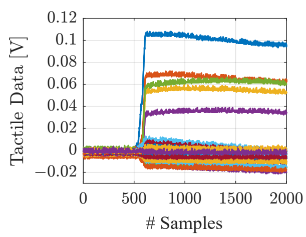
(a)



(b)



(c)



(d)

Fig. 9. Fingers aligned for the grasp (**a**), detail of the fingernails (**b**), wire between the tactile pads (**c**) and tactile signals (**d**).

the scanning approach proposed in [14], with a cruise velocity of 1 cm/s. By using the optimized strategy, the duration is 27 sec in the first experiment and 33 sec in second one, with respect to 167 sec for both experiments if the original strategy was used. The duration is about 5 times shorter. With different cruise velocities the results are similar as detailed in [14].

V. Discussion and Conclusions

The paper showed the characterization of a Time-of-Flight proximity sensor for targets at small distances and, on the basis of this characterization, it presented an optimized scanning strategy which uses the sensor to detect a wire on a workbench and to estimate its pose in the space. The retrieved information is then used to grasp the wire in a desired point. Experiments have been carried out both with the wire raised from the workbench and with the wire lying on it, showing the effectiveness of the proposed strategy. In future works, the height of the workbench will not be considered known, but it will be obtained by using the variations in the tactile sensor signals due to the interaction between the workbench and the fingernails. Moreover, the use of a vision system will be exploited and combined with the proximity sensor to further reduce the scanning time.

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