Unknown Object Manipulation Based on Tactile Information

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***Abstract*— This work proposes an approach to manipulate unknown objects based on tactile information. The manipulation can have three goals: the optimization of the hand configuration, the optimization of the grasp quality and the optimization of the object configuration. Three different motion strategies are introduced in order to move the fingers trying to deal with each of the three goals. The strategies can be applied independently or combined in a sequential way. The feasibility of the motion strategies was proven in real experimentation using the Schunk Dexterous Hand SDH2.**

I. Introduction

Object manipulation using robotic hands equipped with tactile sensors, to detect contacts and increase their capabilities, is a challenging subject in the robotic field. This has impulsed the development of grasping elements with anthropomorphic features, some examples of this elements are the Allegro Hand [1], the Schunk Dexterous Hand [2], the Shadow hand [3], the DLR hand II [4], among others.

Usually, during the object manipulation, it is expected that contact points between the hand and the object are located in specific locations. However, in complex applications the location of the contact points can not be precisely predicted or can not be modeled in advance [5]. In this scenario, tactile information is important for robotic hands since the hands gain in dexterity and precision in object handling when they use tactile feedback. The tactile information obtained during handling can also be used to recognize the shape of unknown objects [6].

The manipulation process usually pursues three goals, one from the hand point of view, one from the grasp (relation hand-object) point of view and one from the object point of view:

- The optimization of the hand configuration: search for a "comfortable" hand configuration while holding the object;
- The optimization of the grasp quality: search for a "secure" grasp such that the hand can resist external force perturbations applied on the object;
- The optimization of the object configuration: search for an "appropriate" object position and orientation to accomplish with the requirements of a given task.

This paper presents an approach to manipulate unknown objects based on tactile information, pursuing these three goals.

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The manipulation of unknown objects has been addressed using different strategies. A method to change the pose of objects of unknown shape using a virtual object frame is introduced in [7], it is based on the triangular fingertip configuration of a three-fingered hand, it also propose a control law to manipulate the object, however the lack of sensorial feedback limits the accuracy of the method. A composite position-force control scheme is presented in [8]. The object relative position with respect to the hand is changed following an input trajectory; the control scheme is evaluated in simulations introducing noise on the sensor measurements to simulate a real environment, however other grasp aspects, as the resulting initial grasp or the stability of the grasp, are not addressed. On the other hand, machine learning techniques have been applied to improve the object manipulation using tactile information, specifically, in order to estimate the grasp stability [9], [10]. Grasp stability can be also achieved using a hybrid force/position controller to perform the grasp of unknown objects by sliding the fingers on the object surface [11]. As a difference with most of the previous works commented above, the proposed approach allows the manipulation pursuing any of the three goals (comfort of the hand, stability of the grasp or object position) as long as their are possible.

The paper is arranged as following. After this introduction, Section II introduces the bases of the addressed problem. Section III discusses the proposed object manipulation approach and the motion strategies to accomplish with the manipulation goals. Experimental results are described in Section IV. Finally, Section V presents the conclusions and future work.

II. Problem Statement

This work is focused on the in-hand manipulation problem, in which an unknown object is grasped and manipulated using a robotic hand. The hand has a tactile sensor system, which offers feedback on the contacts between the hand and the object. The object is unknown, i.e. there is not a priori information about the object shape but it is assumed to be rigid. The tactile sensor feedback combined with the kinematic information of the hand is used to manipulate the object avoiding its fall. The presented approach uses tactile feedback to seek the three goals mentioned in the introduction, i.e. optimizing the manipulation action from the point of view of the hand, the object, and the hand-object relationship. The three goals can be pursued independently or as a sequential combination.

Consider a n-dimensional vectorial space defined by the values of the finger joints. Any movement of the fingers is

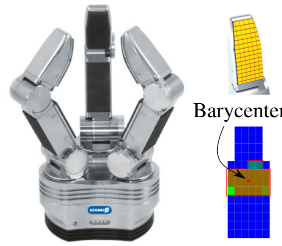

Fig. 1. Schunk Dexterous Hand (SDH2) with seven *dof* and six tactile sensors arrays, detail of a sensor pad, and graphical representation of the sensor data when the fingertip touches an object showing the the contact region and its barycenter.

represented by a curve in this space, whose points indicate the sequence of hand configurations. The manipulation problem can be solved by following an appropriate curve, but finding it is not a trivial problem when the manipulated object is unknown and the manipulation constraints cannot be computed a priori. In this case, planing in advance a precise sequence of movements cannot be done due the lack of information, and therefore it is necessary some exploration method based on on-line sensorial information to find the proper manipulation movements.

The proposed approach deals with the search of the manipulation movements for an unknown object using only the feedback of the tactile information and the hand kinematics, i.e. there is not other information source, like, for instance, visual information. The robotic hand used for the experimentation is the Schunk Dexterous Hand SDH2 [2] shown in Figure 1. This is a three-finger hand with two independent degrees of freedom (*dof*) on each finger, plus another one permitting the rotation of the bases of two fingers allowing them to work opposite to each other in the same plane. The hand has six tactile sensor arrays, one in each phalanx. Each sensor gives information about the relative position of the contact point with respect to the sensor frame, and about the force applied on the object by the corresponding phalanx.

III. Object Manipulation

In this work, the object manipulation is done using two fingertips of the SDH2. The fingers perform a prismatic precision grasp [12], which is comparable with a human grasp using the thumb and index fingers. Thus, the two coupled fingers of the SDH2 are rotated about their bases to work opposite to each other on the same plane. A motion strategy is chosen depending on the goal of the manipulation. The main algorithm and the three motion strategies are introduced in the next subsections.

A. Main Algorithm

Algorithm 1 summarizes the procedure used to manipulate an object using tactile feedback. The manipulation starts with an initial blind grasp, where the fingers start their movements from a wide open position and they are closed on the object until a desired force F^d is reached, then the object is manipulated pursuing the desired goal. Manipulation is an iterative process where each iteration is a manipulation step. Typical end conditions of the manipulation process are: a stop signal is activated, the manipulation goal is reached, the friction constraints are not satisfied or the fingers reach their workspace limits.

Algorithm 1: Manipulation with tactile feedback

Input : F^d

$k = 0$
while $F_k < F^d$ **do**
    Close fingers to grasp the object
    Compute F_k using eq. (1)
while *Stop signal is not activated* **or** *Goal is not reached* **do**
    Compute F_k using eq. (1)
    Compute P_{1_k} and P_{2_k} using Direct Kinematics
    Computed d_{k+1} using eq. (3)
    Compute $P_{1_{k+1}}$ and $P_{2_{k+1}}$ using a Motion Strategy
    if *Friction constraints are satisfied* **and** $P_{1_{k+1}}$ *and* $P_{2_{k+1}} \in$ *workspace of the fingers* **then**
        Move f_1 and f_2 to reach the expected contacts at $P_{1_{k+1}}$ and $P_{2_{k+1}}$
        $k = k + 1$
    else
        Stop signal activated

Once the initial grasp is performed, the absolute positions of the initial contact points are computed using the sensor contact information and the hand kinematics, and they are used as initial conditions for the manipulation process. Consider a global reference system located at the base of the finger f_1, the initial grasp produces two contact points, namely P_1 on finger f_1 and P_2 on finger f_2. Usually the contact with the object produces a contact region, we consider the barycenter of this region as the contact point and the average force over all the region as the contact force, as proposed in [13] (See Figure 1).

The grasping force F_k is computed as the average of both contact forces F_{1_k} and F_{2_k} measured, respectively, by the sensors of each fingertip,

$$F_k = \frac{F_{1_k} + F_{2_k}}{2} \tag{1}$$

where k denotes the manipulation step.

The distance d_k between the contact points is given by,

$$d_k = \sqrt{(P_{x1_k} - P_{x2_k})^2 + (P_{z1_k} - P_{z2_k})^2} \tag{2}$$

Manipulation is based on a reactive control scheme, in which the current information of the contacts and the kinematic information of the hand are used as inputs. The reactive control action is applied to update d_k as a function of the measured force, resulting in the controlled distance d_{k+1} computed as,

$$d_{k+1} = d_k + \Delta d \tag{3}$$

with Δd being a function of the force measured by the tactile sensors according to the follow relationship,

$$\Delta d = \begin{cases} 0 & \text{if } F_{\min} < F_k < F_{\max} \\ +\lambda & \text{if } F_k \leq F_{\min} \\ -\lambda & \text{if } F_k \geq F_{\max} \end{cases}$$

where the constant values $F_{\min}, F_{\max}$ and λ must be empirically determined depending on the sensors response. A complete description of the hand kinematics can be found in [14]. The motion strategies and their quality indexes are discussed in the next subsections. A complete review on grasp quality measures can be found in [15].

B. Motion Strategy 1: Optimizing the hand configuration

When the goal of the manipulation is the optimization of the hand configuration, the joints of the fingers must try to reach the middle-range position avoiding object falls. We consider a quality index Q_{PFC} that favors the hand configurations with the joints as close as possible to the center of their ranges normalized with corresponding joint ranges [16]. Q_{PFC} is given by,

$$Q_{\text{PFC}} = \sum_{i=1}^{l} \left(\frac{\theta_i - \theta_{0i}}{\theta_{\max_i} - \theta_{\min_i}} \right)^2 \tag{4}$$

where l is the number of joints of the hand, θ_i and θ_{0i} are the current and the middle-range positions of the i-th joint, respectively, and, $\theta_{\max_i}$ and $\theta_{\min_i}$ are the maximum and minimum limits of the i-th joint. The minimization of Q_{PFC} allows a grasp configuration with a potential wide range of manipulation, since the hand joints are far away from their mechanical limits.

The next configurations of the fingers are easily computed since the middle and the current positions of the joints are known. In this motion strategy, the fingers change their roles in each manipulation step, between leader and follower. The configuration for the leader finger is computed as,

$$\theta_{j_{k+1}} = \theta_{j_k} + (\text{Sign}(\theta_{j_k} - \theta_{0j}) \times \Delta\theta) \tag{5}$$

where the function $\text{Sign}(x)$ is given by,

$$\text{Sign}(x) = \begin{cases} -1 & \text{if } x < 0 \\ 0 & \text{if } x = 0 \\ 1 & \text{if } x > 0 \end{cases}$$

$\Delta\theta$ is chosen small enough to ensure small changes in the position of the contact point.

The follower finger must adapt its configuration to avoid object falls. We consider the hypothesis that the follower finger moves over a virtual circular path whose radio is given by the distance d_{k+1} resulting from eq. (3), as shown in Figure 2. Given the coordinates of the leader finger (i.e. $P_{1_{k+1}}$ for the first iteration), the coordinates of the follower finger ($P_{2_{k+1}}$) are compute as,

$$P_{z2_{k+1}} = P_{z1_{k+1}} + \left(\tan(\rho) \sqrt{\frac{d_{k+1}^2}{\tan(\rho)^2 + 1}} \right) \tag{6}$$

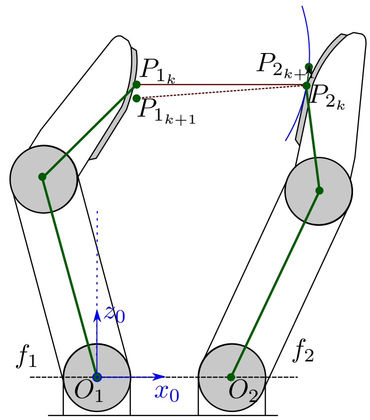

Fig. 2. Two fingers model used for the optimization of the hand configuration.

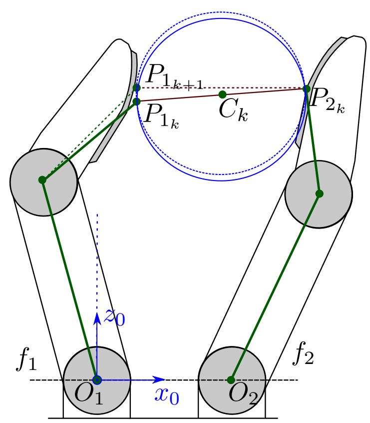

Fig. 3. Two fingers model used for the optimization of the grasp quality.

$$P_{x2_{k+1}} = P_{x1_{k+1}} + \sqrt{d_{k+1}^2 - (P_{z2_{k+1}} - P_{z1_{k+1}})^2} \tag{7}$$

where the angle ρ is computed as,

$$\rho = \arctan \left(\frac{P_{z2_k} - P_{z1_{k+1}}}{P_{x2_k} - P_{x1_{k+1}}} \right) \tag{8}$$

C. Motion Strategy 2: Optimizing the grasp quality

When the goal of the manipulation is to optimize the grasp quality, the hand have to manipulate the object optimizing the current force closure grasp. We use a quality index Q_{DNF} that relates the angle between the normal forces at the contact points and the segment between the contact points. Q_{DNF} favors the finger forces closer to the surface normal. If the segment is close to the boundary of the friction cone, i.e. far from the normal directions, the object could easily slip in presence of perturbations [17]. Q_{DNF} is expressed as,

$$Q_{\text{DNF}} = \frac{1}{n} \sum_{i=1}^{n} |\beta_i| \tag{9}$$

where n is the number of contact points, and β_i is the angle between the normal direction at each contact point and the segment between contact points.

In this motion strategy, we consider the hypothesis that the shape of the object is locally circular, so a proper movement over its shape following the right direction improves the grasp quality. This direction depends on the computed angle β_i for each finger f_i. The fingers have again different roles (leader and follower) and iteratively change them. The new configuration for the leader finger is computed over the hypothetical circular shape of the object, as a displacement over an arc of circumference $(d_{k+1}/2) \times \Delta\phi$ as shown in Figure 3, i.e. the circumference arc between P_{1_k} and $P_{1_{k+1}}$. $\Delta\phi$ can be positive or negative to perform displacements of the contact point in both directions of the fingertip. The sign of $\Delta\phi$ have to be chosen with the same sign of β_i. This displacement is mapped on the sensor surface changing the contact point on the sensor. The next configuration for the leader finger (i.e. $P_{1_{k+1}}$, assuming the leader is f_1) is computed as,

$$P_{x1_{k+1}} = C_{x_k} - (d_{k+1}/2)\cos(\Delta\phi) \quad (10)$$

$$P_{z1_{k+1}} = C_{z_k} - (d_{k+1}/2)\sin(\Delta\phi) \quad (11)$$

where the point C_k is the center of the circumference given by,

$$C_{x_k} = \frac{P_{x2_k} - P_{x1_k}}{2} + P_{x1_k} \quad (12)$$

$$C_{z_k} = \frac{P_{z2_k} - P_{z1_k}}{2} + P_{z1_k} \quad (13)$$

besides, in eq. (10) and eq. (11) $\Delta\phi$ is chosen small enough to assure small movements of the object on each manipulation step. The next configuration of the follower finger ($P_{2_{k+1}}$) is computed using the same procedure as in the Motion Strategy 1.

D. Motion Strategy 3: Optimizing the object orientation

Another possible goal of the manipulation is the improvement of the object position and orientation looking for a desired one. In this work we consider that the absolute position of the object in the space in controlled by the arm, and therefore only the orientation will be controlled by the fingers, i.e. the finger will care about the object orientation assuming that if this implies a change in the object position the arm will take care of it. Let γ be the object orientation. The orientation resulting from the initial grasp is considered as the reference orientation (i.e. $\gamma = 0$). Given a desired orientation γ_d of the object with respect to the one obtained in the initial grasp, the used quality index Q_{ROT} measures the orientation error (i.e. the angle that the object must be rotated to reach the desired orientation),

$$Q_{\text{ROT}} = |\gamma_d - \gamma_k| \quad (14)$$

where γ_k is the current orientation of the object computed from the hand movements in the iteration k. No other external feedback is considered in the procedure (for instance, the object orientation given by a vision system) although it could exist at a higher level.

In this motion strategy we consider the hypothesis that the fingers are moved over a circular path whose diameter is given by the distance between contact points, d_{k+1}, as shown in Figure 4. In this case both fingers are moved at same time,

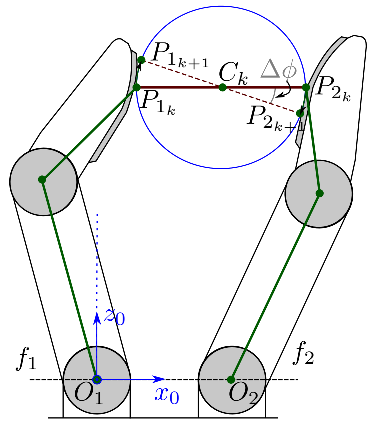

Fig. 4. Two fingers model used for the optimization of the object orientation.

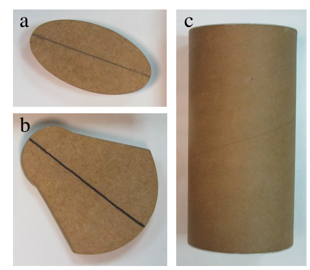

Fig. 5. Three manipulated objects. a) Object 1: elliptical shape; b) Object 2: two-curvature shape; c) Object 3: cylinder.

i.e. they do not have different roles. So, the expected contact points $P_{1_{k+1}}$ and $P_{2_{k+1}}$ are computed as,

$$P_{x1_{k+1}} = C_{x_k} - (d_{k+1}/2)\cos(\Delta\phi) \quad (15)$$

$$P_{z1_{k+1}} = C_{z_k} - (d_{k+1}/2)\sin(\Delta\phi) \quad (16)$$

$$P_{x2_{k+1}} = C_{x_k} + (d_{k+1}/2)\cos(\Delta\phi) \quad (17)$$

$$P_{z2_{k+1}} = C_{z_k} + (d_{k+1}/2)\sin(\Delta\phi) \quad (18)$$

where $\Delta\phi$ is chosen positive to turn the object clockwise or negative to turn the object counterclockwise. $\Delta\phi$ is chosen small enough to assure small movements of the object on each manipulation step. The point C_k is the center of the circumference, and it is computed using eq. (12) and eq. (13).

IV. Experimental Results

The described motion strategies have been fully implemented using C++ for the manipulation of unknown rigid objects with the SDH2 hand. Figure 5 shows some rigid objects used in the experimentation. Due to space constraints, only one example is shown for each motion strategy. Each object is held between the two coupled fingers of the SDH2, then the fingers are closed until the detected contact force reach a desired value $F^d = 2$ N. Note that the initial contact points are unknown, i.e. the initial grasp configuration changes at each execution of the experiment. After this, the object is manipulated by the two fingers following one of the motion strategies proposed in Section III.

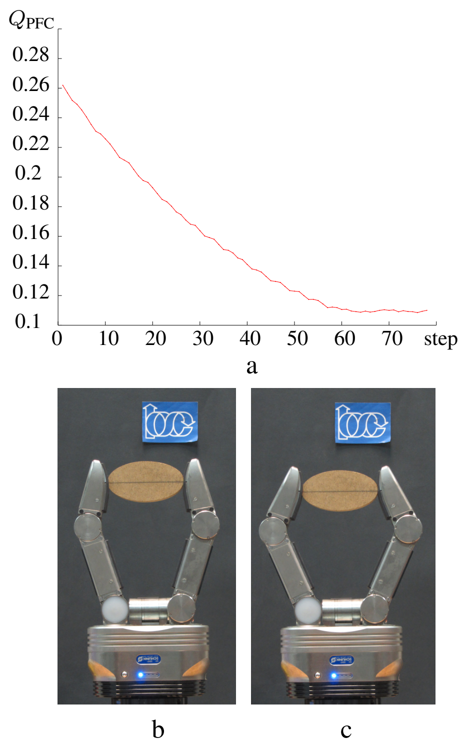

Fig. 6. a) Q_{PFC} resulting of the manipulation of Object 1; b) Snapshot of the initial grasp; c) Snapshot of the final grasp.

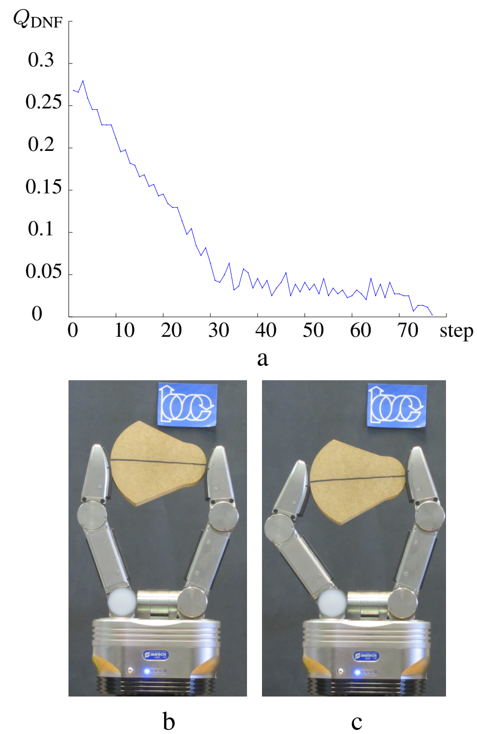

Fig. 7. a) Q_{DNF} resulting of the manipulation of Object 2; b) Snapshot of the initial grasp; c) Snapshot of the final grasp.

The material of the sensor pads is rubber and the material of the objects is wood or cardboard, thus we consider a worst case friction coefficient $\mu = 0.4$, which is lower than the friction coefficient between rubber and wood $\mu = 0.7$, and rubber and cardboard $\mu = 0.5$ [18]. The constant λ to adjust the distance d_k is set to 1 mm.

A. Optimizing the hand configuration

The joints of the SDH2 have a range from -90 to 90 degrees, therefore the middle range is 0 degrees, however when the joints are in the middle position the hand is in a singular configuration, thus in this example, each joint range has been adjusted between -90 and 0 degrees for the proximal joints and, between 0 and 90 degrees for the distal joints. The joint variation in each manipulation step was set to $\Delta\theta = 0.5$ degrees. Figure 6a shows the evolution of Q_{PFC} during the manipulation of Object 1. Note that Q_{PFC} decreases in each manipulation step, which is an indicator of an improvement in the hand configuration. In this case, the manipulation had a duration of 10,31 s, it ended because Q_{PFC} did not improve in the last 15 manipulation iterations. Figure 6b and 6c show snapshots of the initial and final grasp configurations.

B. Optimizing the grasp configuration

Figure 7a shows the evolution of Q_{DNF} during the manipulation of Object 2. The parameter to vary the position of the contact points was set to $\Delta\phi = 0.5$ degrees. The manipulation ends when the angles β_i are below a threshold of 0.1 around zero, this happened at 10,74 s. Figure 7b and 7c show snapshots of the initial and final grasp configurations.

C. Optimizing the object orientation

In this case, Object 3 was rotated as much as possible in both senses. Figure 8a and 8b show the change in the orientation of Object 3, with respect to the initial grasp, when the object was rotated clockwise and counterclockwise, respectively. The manipulation took 5,32 s in the counterclockwise case and 5,53 s in the clockwise. The manipulation ended when one of the fingers reaches its workspace limits in both executions. Figure 8c shows a snapshot of the initial grasp configuration; Figure 8d and 8e show the final grasp configurations when the object was rotated as much as possible counterclockwise and clockwise, respectively.

D. Optimizing the hand and grasp configurations

In this example the goal is the improvement of the hand and grasp qualities, using for it a sequential combination of the corresponding individual strategies. First, the object was manipulated until the quality index Q_{PFC} related to the hand configuration was not improved anymore. Then, the motion strategy to improve the index Q_{DNF} related to the grasp quality was applied, allowing a variation of Q_{PFC} within a given threshold (i.e. it can worsen a limited amount). Figure 9 shows the obtained quality indexes Q_{PFC} and Q_{DNF} when the Object 3 was manipulated. Even when both quality indexes are shown during the whole manipulation process, until iteration 93 only Q_{PFC} was considered as an optimization index, using the corresponding motion strategy. At this point, since Q_{PFC} has not improved for 15 consecutive iterations, the optimization strategy was changed to improve Q_{PFC}, but now checking that Q_{PFC} remains within the given threshold.

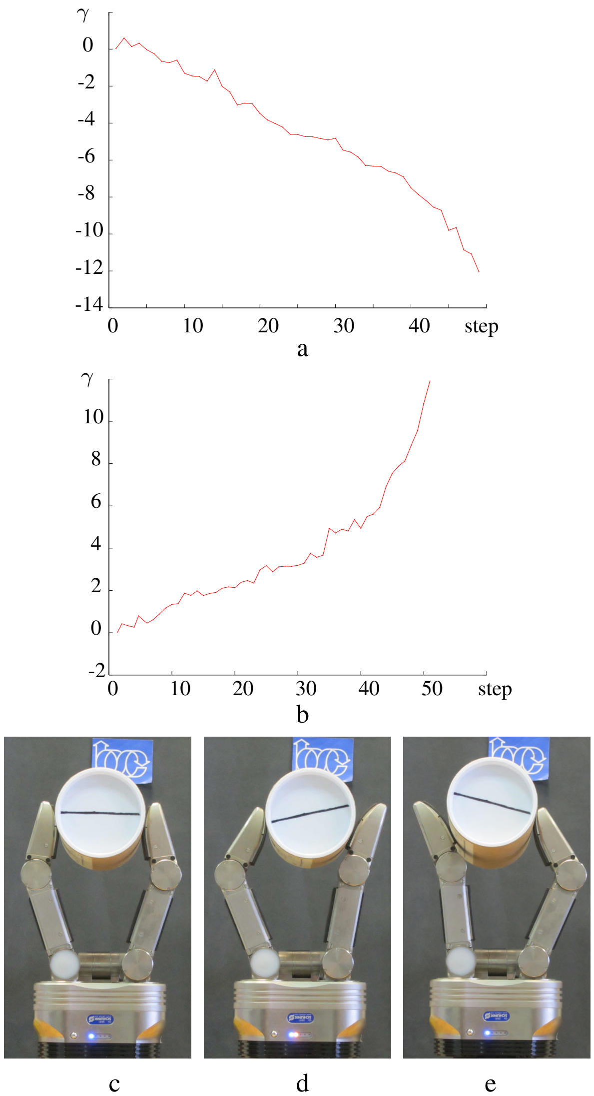

Fig. 8. Orientation resulting of the manipulation of Object 3, when it was rotated a) clockwise; b) counterclockwise. c) Snapshot of the initial grasp. Snapshots of the final grasp when the object is rotated d) counterclockwise; e) clockwise.

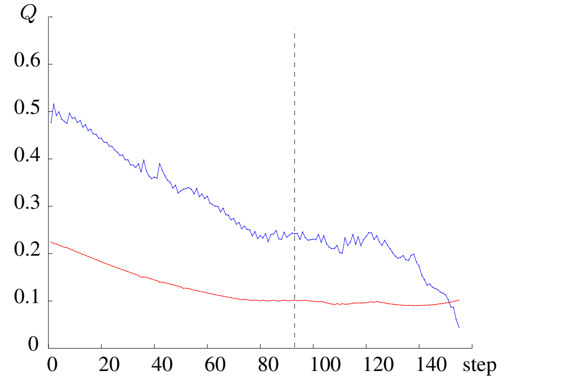

Fig. 9. Q_{PFC} (in Red) and Q_{DNF} (in Blue) resulting from apply the strategies to improve Q_{PFC} until iteration 93, when it has not improved for 10 iterations, then the strategies to improve Q_{DNF} was applied while Q_{PFC} remains within a given threshold.

The manipulation ended when Q_{PFC} reached the accepted threshold value, with Q_{DNF} being less than 0.1, this happened after 28,81 s.

V. Conclusion and Future work

A manipulation approach based on tactile information and reactive control was presented to manipulate unknown objects. The approach also includes three motion strategies to deal with the optimization of the hand configuration, the optimization of the grasp quality, and the optimization of the object configuration. The experimental results showed that the approach is effective to accomplish with these goals.

An extension of the current implementation is to consider the use of three fingers in the manipulation process, which would allow to consider other quality metrics and also new motion strategies.

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