Model-free in-hand manipulation based on commanded virtual contact points

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***Abstract*—This paper presents a simple strategy to allow the rotation of unknown objects using a robotic hand equipped with tactile sensors. The tactile and kinematic information, obtained while that the object is manipulated, is used to determine the hand configurations that change the object position. The approach was successfully tested using an anthropomorphic robotic hand (Allegro Hand), with the fingertips modified to include tactile sensors (WTS-FT). Using three fingers of the hand, every-day objects were successfully rotated without using their model for the determination of the hand movements.**

***Index Terms*—Model-free manipulation, tactile sensing, multi-fingered hand.**

I. Introduction

Dexterous manipulation has been one of the most relevant topics in robotic research during the past years [1]. Commonly, new manipulation strategies are inspired in the human capability to manipulate any kinds of objects in their environment, this fact has led to the development of a wide variety of anthropomorphic robotic hands [2]. Some examples of these hands are the DLR-HIT Hand II [3], the MA-I [4], the Shadow Hand [5], the Schunk Dexterous Hand [6], the Robonaut 2 Hand [7], the Robotiq three-finger gripper [8], the Allegro Hand [9], among others.

Usually object manipulation pursues three main goals: the optimization of the grasp quality, the optimization of the hand configuration and the optimization of the object configuration [10]. In a previous work of the authors, strategies for the manipulation of unknown objects were proposed to improve the grasp quality from the point of view of the hand, the grasp and the task [11]. These strategies where successfully tested using two articulated fingers of an industrial gripper and the manipulation was limited to perform movements in a plane.

The inclusion of tactile sensors into robotic hands increases its capabilities since they allow the obtainment of contact information during the manipulation process [12], as well as the performing of more complex tasks, not only in industrial but also in every-day environments. Object recognition and reduction of uncertainty in the object geometric model are two of the most common tactile sensors applications, where the manipulation is performed even when the object is completely unknown. It must be remarked that the expression "model-free" means that the model of the object is not used at all in the manipulation process.

The manipulation of unknown objects has been addressed from different perspectives. Some of them are centered on hardware design, e.g. studying the capability of fingers to rolling, in order to propose gripper designs that are able to perform dexterous manipulation, at the same time that identify the object surface [13], or designing tactile sensor systems that augment hand capabilities [14]. Others are focused on the manipulation strategies, e.g. decomposing the manipulation problem into small movements that allows the description of a complex task in terms of simpler actions [15], or applying control techniques to model the manipulation problem [16]. On the other hand, vision systems has been used to complement the tactile information in the exploration of unknown objects task [17]. Finally, machine learning approaches has been proposed for the detection of slippage [18], for the object recognition [19], for the adaptation of the grasping motion [20], and for the extraction of manipulation primitives for compliant robot hands [21].

The approach proposed in this work allows the manipulation of an unknown object keeping the grasping forces into a desired range and preventing the object from falling. In this work, manipulation is considered as a reactive procedure whose inputs are the tactile and kinematic data generated during the manipulation. Inspired by human movements when an object is rotated, the proposed approach uses three fingers of a hand to rotate the object forward and backward.

The rest of the paper is organized as follows, Section II introduces the hardware and software set-up used in this work, in particular the robotic hand and the tactile sensor system. The proposed approach and the manipulation algorithm are described in Section III. Experimental results of the manipulation of a set of objects are presented in Section IV. Finally, Section V presents the conclusions and the proposed future work.

II. Hardware set-up

The robotic hand used for experimentation is the Allegro Hand from Wonik Robotics [9]. This is a 4-finger anthropomorphic hand with 4 degrees of freedom (*DOF*) per finger (see Figure 1). The Index, Middle and Ring fingers have the same kinematic structure, the first degree of freedom fixes the orientation of the working plane, the other three are used to

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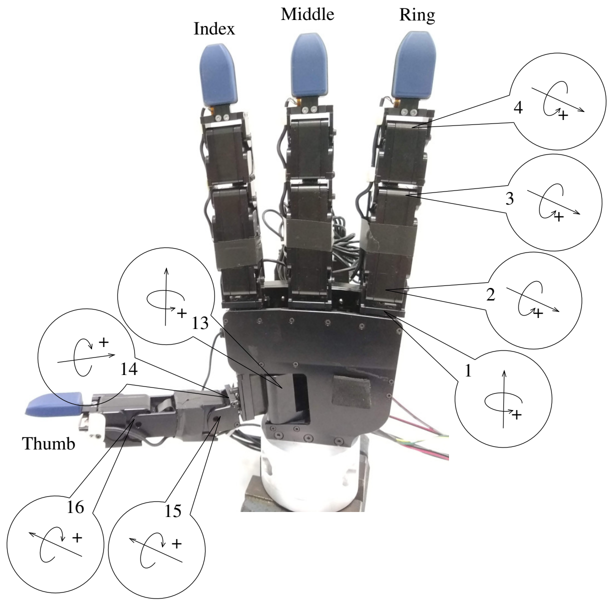

Fig. 1. Anthropomorphic robotic hand Allegro Hand, with 16 *DOF* and 4 fingertips with tactile sensors WTS-FT. Axes of rotation of the joints are indicated; the index, middle and ring fingers have the same kinematic structure. Thumb finger can rotate (abduction movement) over the hand palm.

reach a point and an orientation in this plane. In the case of the Thumb finger, the first degree of freedom produces the abduction movement, the second degree of freedom fixes the orientation of the working plane, leaving only two degrees of freedom to work in this plane, i.e the position and the orientation of the fingertip are not independent.

Each joint of the hand has a DC motor as actuator and a potentiometer to measure its position with a resolution of 0,002 degrees. Connection with a PC is done using a CAN bus. The hand has a low level current based torque control to operate individually each DC motor. Additionally, an external control loop based on a PID control, including gravity compensation, is used to lead the joints to a desired position.

The commercial version of the Allegro Hand does not have tactile sensors, for this reason, in order to increase the capabilities of the hand allowing the obtaining of contact information, the original fingertips have been replaced by sensorized fingertips WTS-FT from Weiss Robotics [22]. The WTS-FT has a tactile sensing matrix with 4×8 texels. The surface of each texel is a square with side length of 3,8 mm. A measurement of the pressure in each texel returns a value between 0, when no pressure is applied, and 4095, for the maximum measurable normal force of 1,23 N. In this work, the contact is modeled using the punctual contact model. However, the contact between each fingertip and the object generally take place over a contact region, therefore, the barycenter of this region is considered as the current contact point, and the summation of the forces sensed at each texel is considered as the current contact force (see Figure 2).

Robot Operating System (ROS) is used as a communication layer that allows the integration of the software modules required for the implementation of the proposed approach: a module to control the Allegro Hand with the implementation of the PID controller, a module to get the measurements of the tactile sensor system, a module with a graphical user interface to command the movements of each joint of the hand to perform the initial grasp, and a module for the manipulation application proposed in this work, as shown in Figure 3.

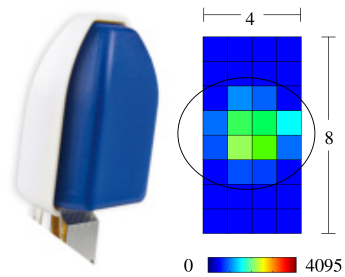

Fig. 2. Tactile sensor WTS-FT with graphical representation of a measurement highlighting with an ellipse the contact region. The bar in the bottom indicates the scale of colors corresponding to the force values returned by each texel.

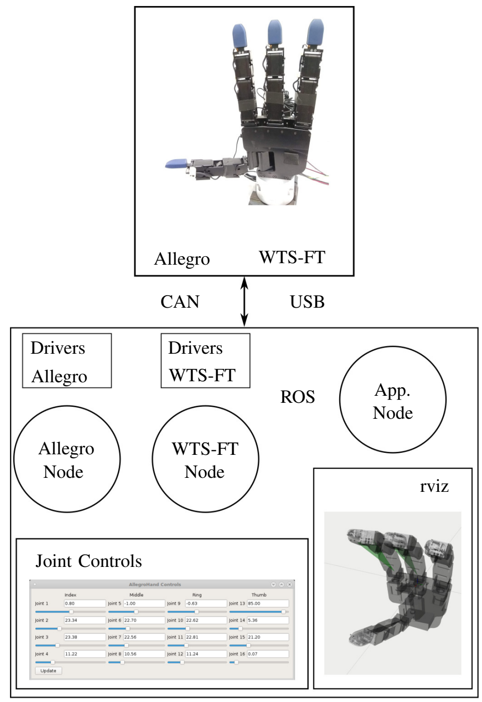

Fig. 3. Hardware and software components overview. Allegro Hand uses a CAN bus for the connection with a PC and WTS-FT sensors in the fingertips use USB. All software components are integrated using Robotic Operative System (ROS) as communications layer.

III. Proposed approach

A. Overview

This work addresses the in-hand manipulation problem of unknown objects. As stated before, the expression ”unknown object” means that none of the object properties (as, for instance, shape, weight and center of mass) are known during the manipulation. Three fingers of a robotic hand are used to grasp and manipulate the object, performing a tripod grasp [23], i.e. the thumb works opposite to other two fingers (abduction movement) in the same way that humans do it. In this work, we will consider that the Thumb works as supporting finger, while the Index and Middle fingers lead the object movements.

It is assumed that the initial grasp is Force Closure grasp [24], but the determination of the initial grasp is outside the scope of this work, it can be determined, for instance, using a generic grasp planner [25], or even by trial an error. Once the object is grasped, the goal of the proposed approach is to compute iteratively the hand configurations that allow the rotation of the object avoiding its fall. Besides, the contact force at each fingertip must remain within a threshold around a desired value. The computation of hand configurations is done using only the tactile (force) and kinematic (finger joint values) information obtained during the manipulation, i.e. no other external feedback sources are considered to obtain information about the object position (like for instance a vision system).

Considering that the fingers work under position control, the hand configurations for the grasping must be such that the commanded positions of the fingertips actually lie inside the object in order to apply a force on the object surface. It must be noted that if the fingertips are positioned exactly on the surface of the object, they will not produce grasping forces on it. From now on, in this work, we will refer to the commanded fingertip positions located "inside" the object as "virtual contact points". Furthermore, the magnitude of the force applied by the fingertip on the object surface depends on the distance between the virtual contact points and the real contact points actually reached on the object surface. Thus, each virtual contact point is adjusted as a function of the force error, which depends on the difference between the desired and current contact forces sensed on each fingertip. Working using only the virtual contact points allows the object manipulation without knowing its real shape.

As stated in Section II, each finger has a working plane associated. In this work the considered manipulation task is the object rotation around the axis parallel to the hand palm plane, which is a movement quite frequently done by humans, thus the finger working planes must be oriented as parallel to each other as possible, as shown in figure 4. Nevertheless, the proposed procedure can be easily applied to rotate the object around any arbitrary axis.

Given a desired object orientation, the manipulation could be done autonomously until that orientation is reached, however, the real current object orientation cannot be computed without an external observer. Thus, in this work, the manipulation commands are continuously provided by the user at a high level, i.e. the goal is, in each iteration, only a single manipulation step in the required direction.

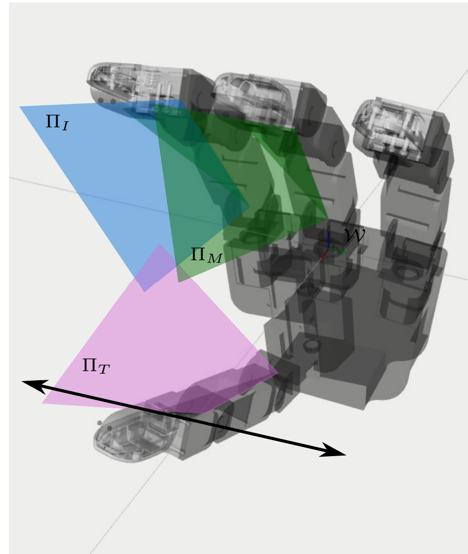

Fig. 4. Allegro hand with the finger working planes for Index, Middle and Thumb. Working planes are oriented as parallel to each other as possible, allowing the object rotation around an axis parallel to the hand palm plane.

B. Proposed Algorithm

A finger f_i, $i \in \{I, M, T\}$ whit I, M and T corresponding to the fingers Index, Middle and Thumb respectively, is a kinematic serial chain with n_i degrees of freedom (*DOF*) and n_i links. Each finger link has a reference frame associated ε_{ij}, $j \in \{1, ..., n_i\}$, to locate its position in the space. The absolute reference frame $\mathcal{W}$ is located at the hand palm. A joint angle q_{ij} relates the position of each link i to the previous one. The finger configuration $\boldsymbol{q}_i$ is given by the concatenation of all the joint angles of the finger as $\boldsymbol{q}_i = \{q_{i1}, \cdots, q_{in_i}\}$. A hand configuration is given by the concatenation of the finger configurations as $\boldsymbol{Q} = \{\boldsymbol{q}_I, \boldsymbol{q}_M, \boldsymbol{q}_T\}$. The finger working planes Π_i are defined by three points corresponding to the positions of the reference frames of the last three finger links. Each Π_i has a reference frame associated Σ_i that coincides with the first reference frame that defines the plane. All the relevant variables for the manipulation are computed using the projections of the relevant points in the working planes of each finger.

The manipulation procedure is an interactive process in which the user must indicate the desired direction of rotation R_k in each iteration k in order to compute the next hand configuration and perform the hand movement. In this work, the indexes k and $k+1$ are used to indicate the current and next iteration, respectively.

The computation of the next virtual contact points $P_{i_{k+1}}$ for the leading fingers (index and middle) is done using an auxiliary point $P^*_{i_{k+1}}, i = \{I, M\}$ which is the resulting point from a displacement $\pm\zeta$ of P_{i_k} on the line perpendicular to the segment between P_{i_k} and the point of rotation fix at P_{T_k}, as shown in Figure 5. $P^*_{i_{k+1}}$ is the resulting point of applying only a motion strategy, but since the shape of the object is unknown, any movement of the fingers may alter the

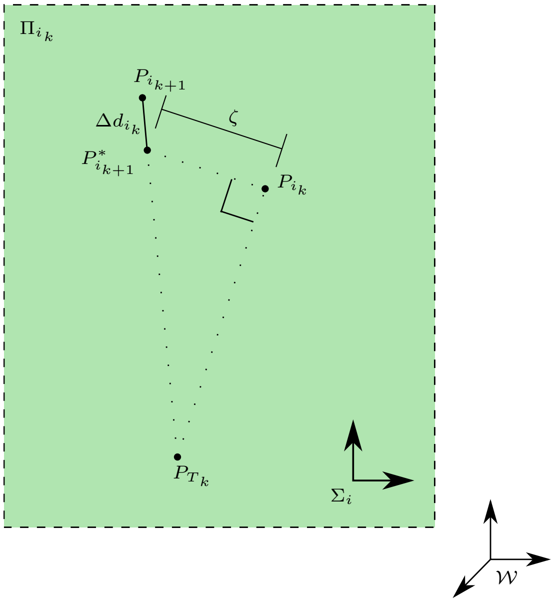

Fig. 5. Example of the computation of $P_{i_{k+1}}, i = \{I, M\}$, in case that the contact force F_{i_k} is larger than F_{i_d} the target virtual contact point $P_{i_{k+1}}$ is moved away applying the adjustment Δd_{i_k}. All points are projected onto Π_{i_k}.

contact force F_{i_k} allowing potential damage of the object or the hand if it increases a lot or allowing a potential fall of the object if it decreases. Therefore, F_{i_k} must remain within a threshold around a desired value F_{i_d}. Thus, in order to reduce the error $e_{i_k} = F_{i_k} - F_{i_d}$ an adjustment Δd_{i_k} in the distance d_{i_k} between the virtual contact points P_{i_k}, $i = \{I, M\}$ and P_{T_k} is computed as

$$\Delta d_{i_k} = \begin{cases} 2\lambda(e_{i_k} + e_{i_k}^2) & \text{if } e_{i_k} \leq 0 \\ -\lambda e_{i_k} & \text{if } e_{i_k} > 0 \end{cases}$$

being λ a predefined constant. The reason for the difference according to the sign of e_{i_k} is that a potential fall of the object ($F_{i_k} \to 0$) is considered more critical that a potential application of large grasping forces ($F_{i_k} \gg F_{i_d}$).

For the computation of the $P_{i_{k+1}}$ of the supporting finger (thumb), it is applied only the adjustment using Δd_{T_k} since the thumb has to keep its configuration, while the index and middle fingers try to rotate the object.

The new hand configuration $\boldsymbol{Q}_{k+1}$ is computed using inverse kinematics (IK) of $P_{i_{k+1}}$. The movement of the fingers is executed only if each $P_{i_{k+1}}$ belong to the workspace of corresponding finger, i.e. the target $\boldsymbol{Q}_{k+1}$ lies within the hand workspace. Algorithm 1 summarizes the main steps of the manipulation procedure.

Algorithm 1: Manipulation algorithm

Inputs : F_{i_d}

k=0
repeat
    Read the direction of rotation R_k
    Compute finger working planes Π_{i_k}
    Project P_{i_k} onto Π_{i_k}
    for i = $\{I,M\}$ **do**
        Compute $P^*_{i_{k+1}}$ according to R_k
        Compute Δd_{i_k}
        Adjust $P^*_{i_{k+1}}$ to obtaint the target $P_{i_{k+1}}$
    Compute Δd_{T_k}
    Adjust the rotating point P_{T_k} to obtain $P_{T_{k+1}}$
    Compute $\boldsymbol{Q}_{k+1}$ from $P_{i_{k+1}}$ using IK
    if $\boldsymbol{Q}_{k+1}$ *belongs to the hand workspace* **then**
        Move the hand to $\boldsymbol{Q}_{k+1}$
    k=k+1
until *stop by user*

IV. Experimental validation

In following illustrative experiments the Allegro Hand fingers were closed around an unknown object, until approximately reaching a desired contact force of F_{i_d}= 5 N. The initial grasp was performed using the graphical application to control individually each hand joint, this application also allows the visualization of the measured force on each sensor at the fingertips. The objects used for experimentation were chosen looking for different shapes, so that the proposed approach performance can be illustrated under different conditions. The constant λ to compute Δd_i was set to 1 mm. The distance ζ to compute the auxiliary points $P^*_{i_{k+1}}$ was set to 1 mm. The manipulation experiment for each object was: first the initial grasp was performed; then the object was rotated clockwise until reaching the limit of the hand workspace; then the object was rotated counterclockwise until reaching again the limit of the hand workspace; finally the object was released and the experiment ended.

Figure 6 shows snapshots of the manipulation of three objects with different shapes: a regular bottle, a bottle with multiple curvatures and a jar with flat faces. From left to right, the first picture shows the user putting the object in the workspace of the hand; the second picture shows the hand performing the initial grasp; the third picture shows the configuration of the hand when the limit of the hand workspace was reached when rotating the object clockwise; and the last picture shows the configuration of the hand when the limit of the hand workspace was reached when rotating the object counterclockwise.

Figure 7 shows the evolution of the commanded and reached finger joint values when the regular bottle (first row in Figure 6) was manipulated. The commanded joint values correspond to the virtual contact points $P_{i_k}, i = \{I, M, T\}$ and the reached joint values are due to the real contact points on the object surface. Figure 8 shows the evolution of the measured forces at the fingertips for this manipulation example. In figures 7 and 8, five regions are remarked using vertical dashed lines and a number inside a circle. The first region shows the joint and force values at the initial hand configuration before

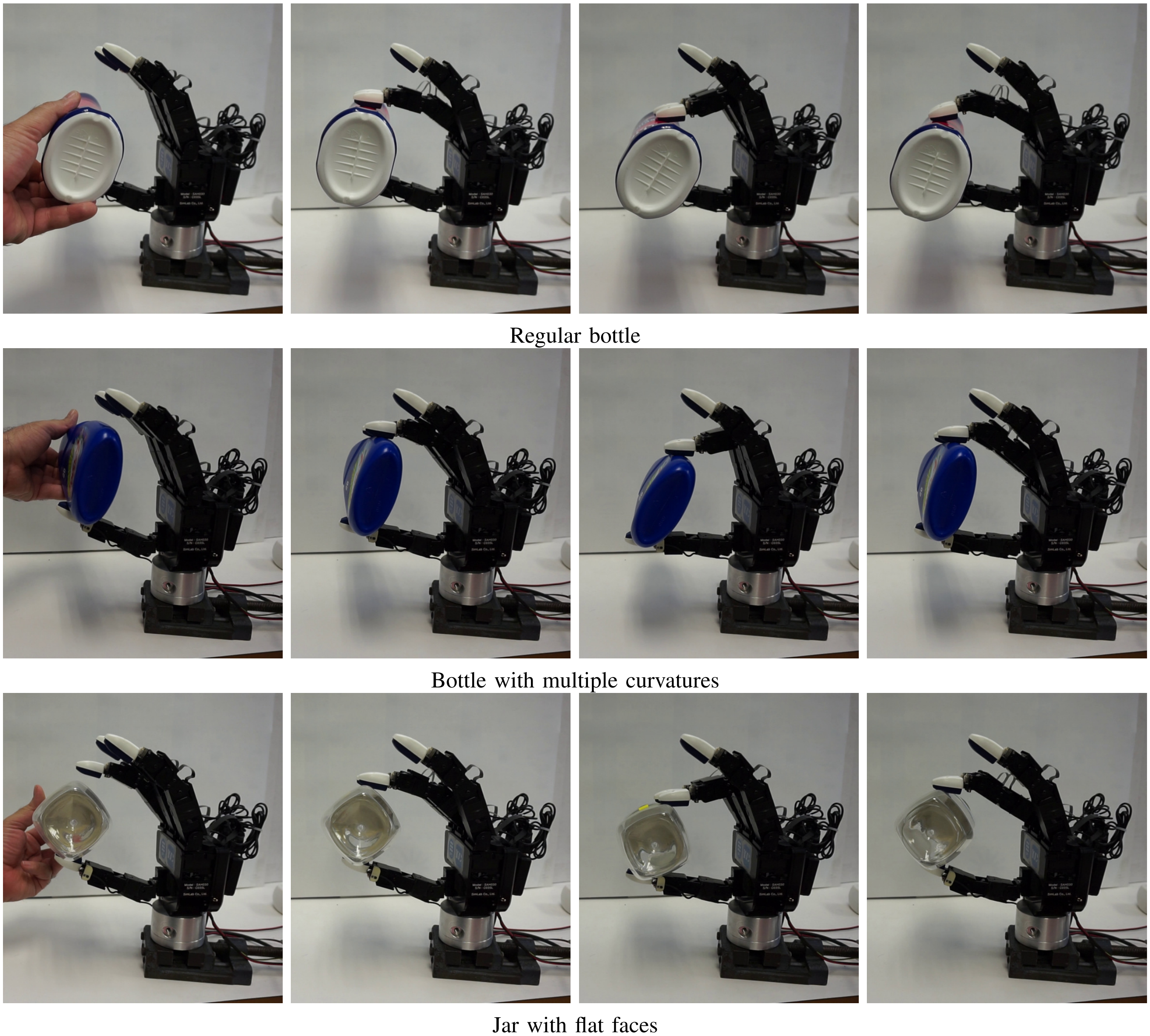

Fig. 6. Snapshots of the manipulation of three objects with different shapes. Objects were rotated clockwise and counterclockwise until reaching the workspace limits of the fingers.

grasping the object; the second region shows the evolution of the values while the initial grasp was performed; the third region shows the evolution of the values while the object was rotated clockwise; the fourth region shows the evolution of the values while the object was rotated counterclockwise; finally, the fifth region shows the values when the object was released and the hand returned to the initial configuration.

Figure 9 and Figure 10, and Figure 11 and Figure 12, show the evolution of the joint values and the measured forces for the other two objects, i.e. when a bottle with multiple curvatures (second row in Figure 6) and a jar with flat faces (third row in Figure 6) were manipulated.

V. Conclusion

A simple but effective manipulation approach based on tactile information and reactive force control was presented to manipulate unknown objects, using three fingers of an anthropomorphic robotic hand. The experimental results shown that the approach is effective to rotate clockwise and counterclockwise objects with different shapes. Although a method to determine the amount of object rotation was not considered, and this is not easily estimated without an external observer, the objects were successfully rotated according to the commands entered by an user.

An natural extension of the proposed approach is to consider the grasp quality control as a goal of the manipulation process.

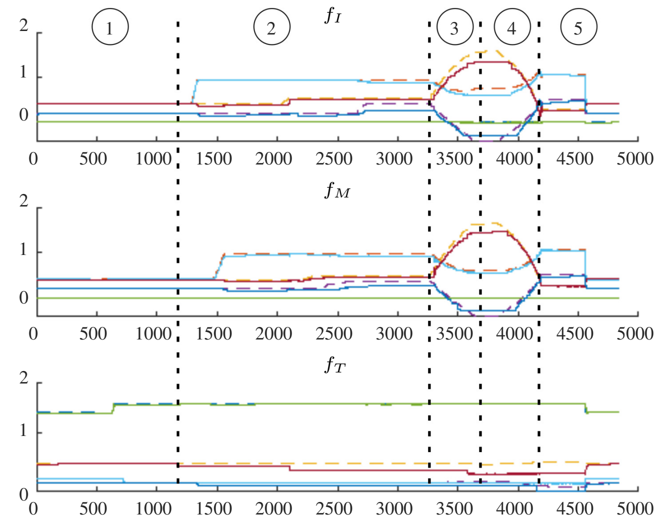

Fig. 7. Evolution of joint values (in Radians) of the three fingers while a larger regular bottle was manipulated. In dashed line, the commanded joints values. In continuous line, the reached joint values.

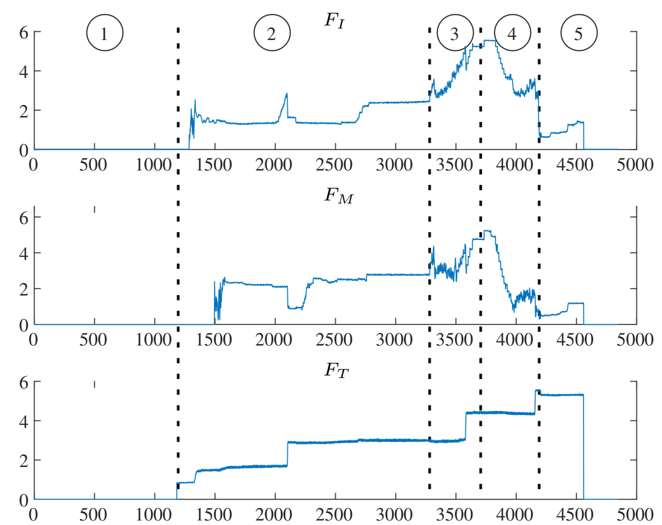

Fig. 8. Evolution of the measured forces (in Newtons) at the fingertips while a large regular bottle was manipulated.

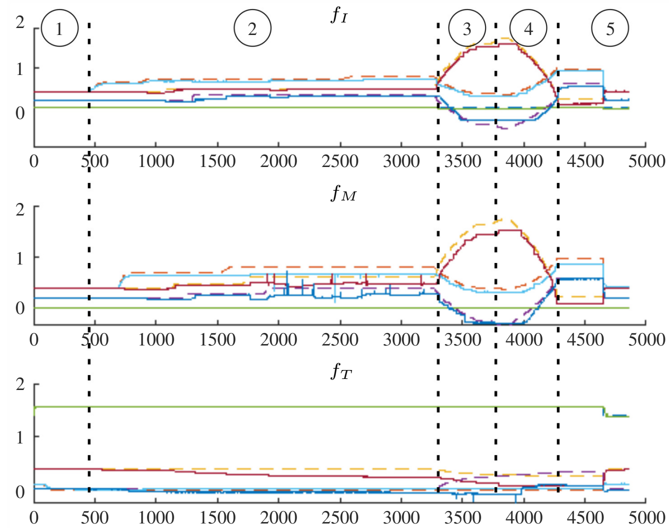

Fig. 9. Evolution of joint values (in Radians) of the three fingers while a bottle with multiple curvatures was manipulated. In dashed line, the commanded joints values. In continuous line, the reached joint values.

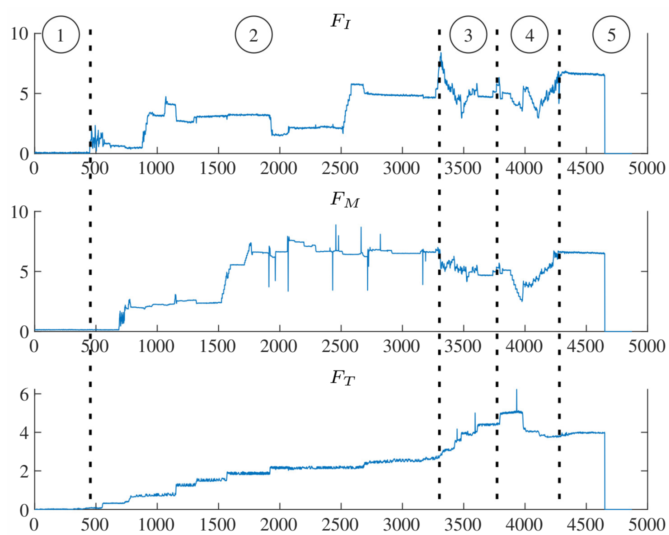

Fig. 10. Evolution of measured forces (in Newtons) at fingertips while a bottle with multiple curvatures was manipulated.

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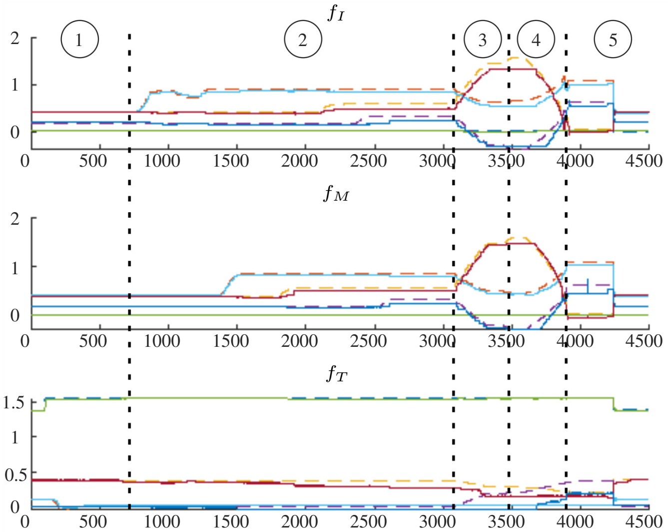

Fig. 11. Evolution of joint values (in Radians) of the three fingers while a jar with flat faces was manipulated. In dashed line, the commanded joints values. In continuous line, the reached joint values.

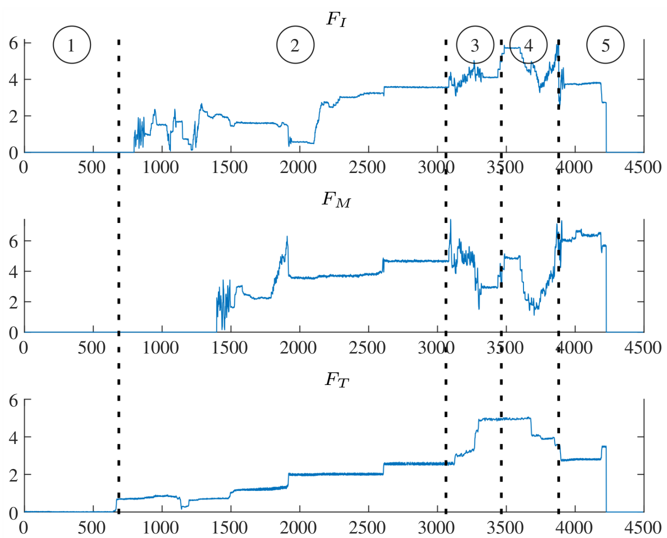

Fig. 12. Evolution of the measured forces (in Newtons) at fingertips while a jar with flat faces was manipulated.

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