Getting comfortable hand configurations while manipulating an object

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Abstract—The paper presents an approach to manipulate unknown objects based on tactile information and force feedback. The object manipulation is performed using two fingers of the Shunck Dexterous Hand, which is equipped with tactile sensors on the fingertips. The contact point on each fingertip is modeled using a virtual articulation which adds a virtual degree of freedom to the finger. The approach uses the tactile data and hand kinematics information in order to estimate a grasp quality measure and to make finger adjustments after an initial grasp in order to improve the hand comfort. The approach was implemented in a real sensorized hand, and some examples manipulating different objects are presented in the paper showing the evolution of the resulting quality.

I. INTRODUCTION

Dexterous manipulation is the capability to change the position and orientation of an object with respect to the hand while keeping a stable grasp [1]. Dexterous manipulation is closely related with the development of grasping elements, some of them with anthropomorphic characteristics [2], [3], [4], [5], [6]. Tactile information is important for robotic hands in order to achieve dexterity and precise object handling.

A task example that requires dexterous manipulation could be the opening and closing of the screw cap of a bottle using the fingers without changing the wrist position. Usually, during the object manipulation, it is expected that contact points between the hand and the object are located in specific locations. However, in more complex applications the location and nature of the contact points can not be precisely predicted or can not be modeled in advance [7].

Object manipulation using robotic hands equipped with tactile sensors to detect contacts and increase their capabilities is a challenging subject. This paper presents an approach to manipulate unknown objects based on tactile information and force feedback.

Robot grasping and manipulation require very accurate knowledge of the location of the object within the robotic hand. A vision system could not provide very precise and robust pose tracking due to occlusions or light limitations. For this reason, visual information has been combined with kinematics and tactile information in order to estimate the pose of a grasped object [8]. The tactile information can be treated as a sequence of images in order to extract information about the contact conditions between an object and the hand [9], and therefore image processing techniques are used to process the tactile sensor information. On the other hand, machine learning techniques have been also applied in order to improve object manipulation using tactile information, specifically, in order to estimate the grasp stability [10], [11]. In a previous work [12] the shape of an unknown object was recognized using manipulation and tactile information obtained during handling.

As a difference with most of the previous works commented above, in this work the dexterous manipulation is performed without previous information about the grasped object, the tactile information provided by the sensors is combined with the hand kinematic information in order to estimate the grasp quality. The changes in the grasp quality define the movements of the fingers in order to manipulate the unknown object, i.e., the manipulation strategy is defined considering the grasp quality to change the grasp pose in order to improve the comfort of the hand. A grasp is considered comfortable if the hand joints are close to the center of their ranges, which also allows a wide set of future movements. Thereby, a manipulation task can be completed using this wide set of movements. Besides, the paper presents a kinematics model of the robotic hand that includes the tactile sensor on the fingertips. The model uses a virtual link in order to include the contact point information, this virtual link adds an extra dof to each finger.

The remainder of the paper is organized as follows. After this introduction, Section II introduces the bases of the proposed approach. In Section III descriptions of the hand

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kinematics and the friction constraints are presented. The bases of the object manipulation approach are discussed in Section IV. Experimental results are described in Section V. Finally, Section VI presents the conclusions and future work.

II. APPROACH OVERVIEW

The robotic hand used in this work is the Schunk Dexterous Hand (SDH2) shown in Figure 1. This is a three finger hand with seven active degrees of freedom (dof). The SDH2 has tactile sensors attached to the surfaces of the proximal links and the distal links (fingertips), thus the tactile sensor system has six sensor pads. Two fingers of the hand are coupled and can be rotated on the base to work opposite to each other in the same plane (see Figure 1). To manipulate an unknown object, the fingertips of the two coupled fingers of the robotic hand are used to perform a prismatic precision grasp [13], which is comparable with a human grasp using the thumb and index finger, thus only the two sensor pads of the fingertips of the coupled fingers are used. The manipulation strategy must guarantee hand configurations which change the relative pose between the object and the hand avoiding object falls, and also improve the comfort of the hand.

Each fingertip tactile sensor of the hand 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 fingertip. Once the object is grasped, the position of the contact points, the distance between the contact points on each fingertip, the contact force, and the grasp quality, are computed using the contact information of both tactile sensors. This information will be used to determine the proper object manipulation, which must avoid the object falls and look for a comfortable hand configuration.

After each manipulation step, the fingers are relocated and as a consequence the grasp quality measure is modified. One of the objectives of the proposed approach is to improve the grasp quality via the object manipulation. The proposed manipulation strategy searches for the movements of the hand that improve the grasp quality in each manipulation step. Consider a search space defined by the position of the finger joints. The movement direction that improves the grasp quality is defined by the gradient of the grasp quality function (ascendant or descent depending on the case). Figure 2 shows a virtual example of the contours of a grasp quality function for a two dof (θ1 and θ2) robot hand. Quality is represented by concentric circles, it increases from the external contour towards the more centric contour. The black line represents the configurations of the hand during an object manipulation, in this example the manipulation starts at the configuration determined by the point (0,50) and it evolves to the point (50,50). The first five hand configurations are around the same contour so they have approximately the same quality, and then the following hand configurations move to inner contours meaning an improvement in the grasp quality.

III. HAND KINEMATICS

The tactile sensor pad on each proximal link of the SDH2 has 84 (6 × 14) tactile sensor cells of 3.4 mm × 3.4 mm while the pad over each fingertip has 70 (4 × 4 + 6 × 9) cells. When the fingertips touch an object the contact is in general produced on a contact area, in this work the contacts are considered to be punctual and the contact points are considered to be located at the barycenter of the contact area on the sensor pad. Thus, the two contacts are represented by the points P1 on finger f1 and P2 on finger f2.

A. Direct Kinematics

The aim of the direct kinematics is to find the position of a potential contact point P1 given the joints values θ2 and θ3 considering the shape of the fingertip and the geometry of the finger. Denavit-Hartenberg parameters [14] are used to describe the kinematic model of the fingers. Each finger has a reference system at the finger base. Figure 3a shows the reference systems used to compute the DH-parameters for the finger f1. The distance between the reference systems of the fingers f1 and f2 is 66 mm along axis-x10. The reference system of the finger f1 is the global reference system. Table I shows the DH-parameters for finger f1, where joint 4 refers to a virtual link from the last finger joint to the contact point. The reasoning for the finger f2 is the same as the described for finger f1. The range of all the joints excepting the coupled joint is from −90 to +90 degrees (See Figure 4). For the coupled joints the range is from 0 to 90 degrees, being 90 degrees the used value to work with the finger is an opposite way.

Since the tactile sensor of each fingertip is not planar, the shape of the sensor needs to be considered in order to compute the position of the potential contact point in the absolute reference frame. The sensor surface is composed of two parts, an arc of a circle with radius 60 mm centered at point K = (33.5, −45) in the reference system x3y3, and a segment of a straight line as seen in Fig.3b. The processing of a sensor
measurement during contact gives the position \((cg_x, cg_y)\) of the barycenter of the contact area in the sensor reference system. In this work only the \(x\) component, \(cg_x\), is considered since the manipulation is performed in the plane \(xy\) and the \(y\) component, \(cg_y\), does not add relevant information. Given \(cg_x\), the coordinates of the contact point \(P_1\) in the reference system \(x_3y_3\) are given by,

\[
P_{1x} = \begin{cases} 17.5 + cg_x \\ 33.5 + 60\sin\left(\frac{cg_x - 16}{60}\right) \end{cases} \quad \text{if} \ cg_x < 16 \\
\begin{cases} 15 \\ -45 + \sqrt{60^2 - (P_{1x} - 33.5)^2} \end{cases} \quad \text{if} \ 17.5 \leq P_{1x} \leq 33.5 \\
\begin{cases} 86.5s\theta_2 + r_1c\theta_2c(\theta_3 - \varphi_1) - s\theta_2s(\theta_3 - \varphi_1) \\ 86.5c\theta_2 + r_1(-c(\theta_3 - \varphi_1)s\theta_2 - c\theta_2s(\theta_3 - \varphi_1)) \end{cases} \quad \text{if} \ P_{1x} \geq 66.4
\]

As mentioned above, a virtual link is used in order to include the contact point information. This virtual link adds an extra \(dof\) to the finger. The reference system \(x_3y_3\) is added at the barycenter of the contact area. The distance \(r_1\) between the origins of the reference systems \(x_3y_3\) and \(x_4y_4\), and the angle \(\varphi_1\) between the \(y_3\)-axis and virtual link described by \(r_1\) are used to include the contact point information. \(r_1\) and \(\varphi_1\), referenced to the \(x_3y_3\) frame, are given by,

\[
r_1 = \sqrt{P_{1x}^2 + P_{1y}^2} \tag{3}
\]

\[
\varphi_1 = \arctan\left(\frac{P_{1x}}{P_{1y}}\right) \tag{4}
\]

The position of the contact point \(P_1\) and the point \(C_1\) the origin of the frame \(x_3y_3\), referenced to the finger frame, can be computed using the values of \(r_1\) and \(\varphi_1\), and the joint values \(\theta_2\) and \(\theta_3\) as,

\[
P_1 = \begin{bmatrix} 86.5s\theta_2 + r_1c\theta_2c(\theta_3 - \varphi_1) - s\theta_2s(\theta_3 - \varphi_1) \\ 86.5c\theta_2 + r_1(-c(\theta_3 - \varphi_1)s\theta_2 - c\theta_2s(\theta_3 - \varphi_1)) \end{bmatrix} \tag{5}
\]

\[
C_1 = \begin{bmatrix} 86.5s\theta_2 \\ 0 \end{bmatrix} \tag{6}
\]

\section*{B. Inverse Kinematics}

The inverse kinematic problem appears when, given the absolute position of the contact point \(P_1\), \(r_1\) and, \(\varphi_1\), it is necessary to find the values of \(\theta_2\) and \(\theta_3\) to properly contact at \(P_1\) (the same reasoning is applied to finger \(f_2\)). There are different approaches to compute the inverse kinematics, in this work we use a geometric approach since the manipulation is done on a plane and using two \(dof\) per finger. Figure 5 shows the geometric parameters used to solve the inverse kinematics.
problem. The values of the angles $\rho$, $\sigma$ and $\gamma$ are computed using the cosine law as,

$$\rho = \arccos \left( \frac{-|O_1 P_1|^2 + |O_1 C_1|^2 + |C_1 P_1|^2}{2|O_1 C_1||C_1 P_1|} \right)$$ (7)

$$\sigma = \arccos \left( \frac{-|C_1 P_1|^2 + |O_1 C_1|^2 + |O_1 P_1|^2}{2|O_1 C_1||O_1 P_1|} \right)$$ (8)

$$\gamma = \arctan \left( \frac{P_{1z}}{P_{1x}} \right)$$ (9)

There are two possible solutions for a given $P_1$, however, considering the geometric constraints imposed by the manipulation problem where the desired configuration belongs to the section workspace which permits that the finger works opposed to the other finger, thus, valid configurations are obtained only for values of $\theta_3$ satisfying $\theta_3 > \varphi_1 - \pi/2$. Then, the values for $\theta_2$ and $\theta_3$ are given by,

$$\theta_2 = -\sigma - \gamma + \text{sign}(P_{1x})\pi/2$$ (10)

$$\theta_3 = \rho - \pi/2 - \varphi_1$$ (11)

where

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

C. Friction Constraints

In order to avoid sliding, each force applied on the object must be located within the friction cone centered at the direction normal to the object surface at the contact point. A planar grasp with two frictional contact points is force-closure when the segment connecting the contact points lies inside the friction cone at both contact points (see Figure 6). The friction cone is given by $\alpha = \arctan \mu$, with $\mu$ being the friction coefficient (Coulomb friction model). Any applied force that belongs to the friction cone will not produce slippage, therefore the angle $\beta_i$, $i = 1, 2$, between the normal direction at each contact point and the segment between the two contact points must satisfy $\beta_i \leq \alpha$. Then, the above condition can be expressed as,

$$\frac{\pi}{2} - \alpha \leq \omega_i < \frac{\pi}{2} + \alpha$$ (12)

where $\psi_i$, $i = 1, 2$ is computed for both contact points as,

$$\psi_1 = \arccos \left( \frac{-|C_1 P_2|^2 + r_1^2 + |P_1 P_2|^2}{2r_1|P_1 P_2|} \right) - \theta_3 - \frac{\pi}{2} + \varphi_1$$ (13)

$$\psi_2 = \arccos \left( \frac{-|C_2 P_1|^2 + r_2^2 + |P_1 P_2|^2}{2r_2|P_1 P_2|} \right) - \theta_3 - \frac{\pi}{2} + \varphi_2$$ (14)

IV. Object Manipulation

To initially grasp an object, the fingers start their movements from a wide open position and they are closed over the object until the desired $F^*\theta$ is reached. The fingers perform a prismatic precision grasp using the fingertips. So, the initial contact points on the object are unknown and they change in each different execution of the manipulation process for the same object. Once the initial grasp is performed, the initial contact points are computed using the contact information as described in the previous section, and they are used as the initial conditions for the manipulation process. The grasping force $F_k$ is computed as the average of the contact forces $F_{1k}$ and $F_{2k}$ measured by the sensors of both fingertips,

$$F_k = \frac{F_{1k} + F_{2k}}{2}$$ (15)

where $k$ denotes a manipulation step.

Another important variable of the contact information is the distance $d_k$ between the contact points $P_{1k}$ and $P_{2k}$, which is given by,

$$d_k = \sqrt{(P_{1kx} - P_{2kx})^2 + (P_{1ky} - P_{2ky})^2}$$ (16)

Different quality metrics can be used to value a grasp configuration. In this work we consider a comfort quality index, $Q_c$, to evaluate the grasp quality during the manipulation process. This quality index, associated with the hand configuration, favors the hand configurations with the finger joints as far as possible from their physical limits, i.e., with the joint positions as close as possible to the center of their ranges [15]. A complete survey on grasp qualities measures can be found in [16], [17]. The used comfort quality index $Q_c$ is given by,

$$Q_c = \sum_{i=1}^{nm} \left( \frac{\theta_i - \theta_{0i}}{\theta_{max,i} - \theta_{min,i}} \right)^2$$ (17)
where $\theta_i$ and $\theta_{oi}$ are the actual and the middle-range positions of the i-th joint, respectively. The minimization of $Q_c$ implies a grasp configuration with the joint positions close to the middle-range reference position.

Algorithm 1 summarizes the procedure used to manipulate an object using tactile feedback. It requires as input the desired force $F^d$ to be applied to the grasped object. First, the fingers are closed until the contact force $F_k$ for $k = 0$ reaches the desired contact force $F^d$ and therefore an initial grasp is performed. Once the object is grasped by the fingertips, the manipulation starts, this is an iterative process that is repeated while a stop signal is not activated or the grasp quality worsens.

The expected contact point $P_{2k+1}$ is computed as a point on a circumference of diameter $d_{k+1}$, which is measured from the contact point $P_{1k+1}$. $P_{2k+1}$ changes the object inclination in $\Delta\alpha_{k+1}$ (See [12] for a detailed description). Finally, the joint values for finger $f_2$ are computed using the inverse kinematics. A similar procedure is applied when $f_2$ is the independent finger.

The angles $\psi_1$ and $\psi_2$ used to verify the friction constraints are computed using the expected contact points. If the friction constraints at $P_{1k+1}$ and $P_{2k+1}$ are satisfied (Eq. 12), and the points $P_{1k+1}$ and $P_{2k+1}$ lie inside the finger workspaces, then, the fingers $f_1$ and $f_2$ are moved such that the contact points on the fingertips currently at $P_{1k}$ and $P_{2k}$ move to $P_{1k+1}$ and $P_{2k+1}$, respectively, and a new iteration is started; else the hand cannot move to the desired position and the manipulation ends.

Algorithm 1: Manipulation with tactile feedback

<table>
<thead>
<tr>
<th>Input</th>
<th>$F^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k = 0$</td>
<td></td>
</tr>
<tr>
<td>while $F_k &lt; F^d$ do</td>
<td></td>
</tr>
<tr>
<td>Close fingers in order to grasp the object</td>
<td></td>
</tr>
<tr>
<td>Compute $F_k$ using eq. (15)</td>
<td></td>
</tr>
<tr>
<td>while Stop signal is not activated do</td>
<td></td>
</tr>
<tr>
<td>Compute $F_k$ using eq. (15)</td>
<td></td>
</tr>
<tr>
<td>Compute $P_{1k}$ and $P_{2k}$ using Direct Kinematics</td>
<td></td>
</tr>
<tr>
<td>Compute $d_k$ using eq. (16)</td>
<td></td>
</tr>
<tr>
<td>Compute $Q_{c_k}$ using eq. (17)</td>
<td></td>
</tr>
<tr>
<td>if $Q_{c_k}$ worsens then</td>
<td></td>
</tr>
<tr>
<td>Move $f_1$ and $f_2$ to contacts at $P_{1k-1}$ and $P_{2k-1}$</td>
<td></td>
</tr>
<tr>
<td>Stop signal activated</td>
<td></td>
</tr>
<tr>
<td>else</td>
<td></td>
</tr>
<tr>
<td>Compute $d_{k+1}$ using eq. (18)</td>
<td></td>
</tr>
<tr>
<td>Compute $P_{1k+1}$ and $P_{2k+1}$</td>
<td></td>
</tr>
<tr>
<td>if Friction constraints are satisfied and $P_{1k+1}$ and $P_{2k+1}$ ∈ workspace of the fingers then</td>
<td></td>
</tr>
<tr>
<td>Move $f_1$ and $f_2$ to reach the expected contacts at $P_{1k+1}$ and $P_{2k+1}$</td>
<td></td>
</tr>
<tr>
<td>$k = k + 1$</td>
<td></td>
</tr>
<tr>
<td>else</td>
<td></td>
</tr>
<tr>
<td>Stop signal activated</td>
<td></td>
</tr>
</tbody>
</table>

V. EXPERIMENTAL RESULTS

In order to illustrate the performance of the proposed approach, the results of manipulating three different objects are presented (see Figure 7). Each object is held between two fingers of the SDH2, then the fingers are closed until the detected contact forces reach the desired value (note that the initial contact points are unknown). After this, the object is
manipulated by the two fingers. The material of the surface of the fingertips 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 of between rubber and wood $\mu = 0.7$, and rubber and cardboard $\mu = 0.5$ [18].

The constant $\lambda$ to adjust the distance between contact points is set to 1 mm, and the desired grasp force $F^d$ is set to 20 $\mu$N, both values were determined empirically. The variation of the finger joints in each manipulation step was set to 0.5 degrees.

Figure 11 shows snapshots of the manipulation of the cylindrical object (Shown in Figure 7(left)). The hand starts in a wide open configuration to be able to grasp a wide set of objects. The object is grasped by closing the finger of the hand. The initial grasp configuration changes at each execution of the experiment. Then, the manipulation starts and the hands moves to a more comfortable configuration. Figure 8 shows the obtained comfort quality index for the manipulation of the cylindrical object. Note that comfort quality index decreases in each manipulation step, which is an indicator of an improvement in the grasp quality. Figure 9 shows the joints of this hand for the manipulation of the same object, which start far from the center of the joint range and evolve towards the center of the range (0 degrees) in order to improve the grasp quality.

Figure 12 shows snapshots of the manipulation of the elliptical object in Figure 7(center). Figure 10 shows the quality index for the manipulation. The evolution of the joints during the manipulation are shown in Figure 14. The behavior of the joints is similar to the obtained when a cylindrical object is manipulated.

Similar results are obtained for the manipulation of a two-curveds object. Figure 13 shows snapshots of the manipulation of the object in Figure 7(right). Figure 15 shows the variation of the quality index and Figure 16 shows the evolution of the joints.

VI. CONCLUSION AND FUTURE WORK

An approach to get comfortable hand configurations while manipulating unknown objects based on tactile information and force feedback was presented. The experimental results showed that the approach is effective to improve the grasp quality for different objects.
Fig. 11. Snapshots of a cylindrical object manipulation. a) Initial hand configuration. b) Initial grasp of the cylindrical object. c) Intermediate manipulation step. d) Final hand configuration with the best comfort quality.

Fig. 12. Snapshots of an elliptical object manipulation. a) Initial grasp. b)-c) Intermediate manipulation step. d) Final hand configuration.

Fig. 13. Snapshots of a cylindrical object manipulation. a) Initial grasp. b)-c) Intermediate manipulation step. d) Final hand configuration.
An extension of the implemented work is the inclusion of other grasp quality measures or a combination of them, which consider different grasp characteristics. The gradient of the comfort quality measure is well known, since the more comfortable configuration is in the center of the hand joint range, but with other grasp qualities the gradient must be computed at same time that the manipulation is performed.

**REFERENCES**


