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Sensitive Manipulation: manipulation through tactile feedback

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Object grasping and manipulation in robotics has been largely approached using visual feedback. Human studies on the other hand have demonstrated the importance of tactile and force feedback to guide the interaction between the fingers and the objects. Inspired by these observations we propose an approach that consists in guiding a robot's actions mainly by tactile feedback, with remote sensing such as vision, used only as a complement. Directly sensing the interaction forces between the object, the environment, and the robot's hand enables it to obtain information relevant to the task that can be used to perform it more reliably. This approach (that we call Sensitive Manipulation) requires important changes in the hardware and in the way the robot is programmed. At the hardware level we exploit compliant actuators and novel sensors that allow to safely interact and detect the environment. We developed strategies to perform manipulation tasks that take advantage of these new sensing and actuation capabilities. In this paper we demonstrate that using these strategies the humanoid robot Obrero can safely find, reach and grab unknown objects that are neither held in place by a fixture nor placed in a specific orientation. The robot can also make insertions by "feeling" the hole without specialized mechanisms such as a remote center of compliance.

Keywords: Humanoid Robot; Robotic Manipulation; Tactile Sensing; Sensitive Manipulation; Biomimetic Manipulation.

1. Introduction

Tactile sensing is essential in how humans interact with their environment and their ability to operate. For instance, subjects had objects slip when their fingers were anesthetized [1] suggesting that sensing the interaction with the environment through physical contact, using a large number of innervations, is key for humans to perform dexterous manipulation tasks. In order to make use of this feedback humans first come in contact with the object to manipulate. The information obtained through contact allow us to learn from an object using Exploratory Procedures (EP) [2] and control our physical interaction with it [3]. Examples that show how we use the tactile feedback include: repositioning their hands and fingers around an object, grabbing and lifting an object stably (without slippage), and placing an object on a surface.

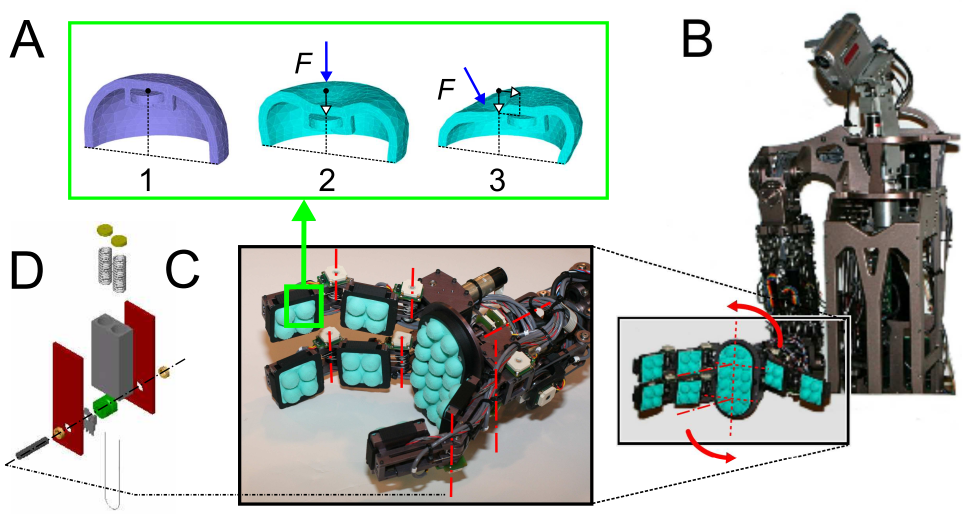

Fig. 1. The robot Obrero. **(A)** The sensors were biomimetically inspired by the ridges and innervations of the human skin. A1 displays a cross-sectional cut of the silicone rubber sensor. A2 and A3 show the deformation from an applied force. The position of the sensor's center is used to estimate the force applied. **(B)** Obrero has a 2 degree of freedom (DOF) head, a 6 DOF arm, and a 8 DOF hand. **(C)** The hand has two fingers and a thumb. The thumb and the middle finger can rotate 90° as shown in (B). Each finger has two phalanges with miniature series elastic actuators **(D)**, which are coupled and driven by one motor. However, the motion of the phalanges can be decoupled when the distal one is locked. There are 16 tactile sensors (each 15mm in diameter) in the palm and 4 in each phalange.

Tactile feedback is considered important for robotics manipulation and a large body of work has been dedicated to the many aspects related. One of the aspects is the development of tactile sensors that has been addressed using a number of different technologies [4,5,6,7,8,9]. A second aspect is the use of compliance elements for soft contact [10,11,12] and conformational grasping [13,14,15]. Another aspect is the algorithms and strategies developed to perform tasks using tactile feedback and compliance elements [16,17,18,19,20,21,22,23,24]. The idea behind these approaches is that directly sensing the interaction forces between the object, the environment, and the hand enables the robot to obtain information relevant to the task. This contact information can be can be used to perform manipulation tasks more reliably.

It is worth stressing that the study of exploratory and grasping strategies that take advantage of tactile feedback may have beyond humanoid robotics. An example is the control of hand exoskeletons [25,26], in which autonomous control driven by tactile feedback could complement neural control and achieve skilled object manipulation.

In this paper, we build on these concepts to perform a number of different manipulation tasks based on tactile feedback. We called this approach Sensitive Manipulation [27] and addresses the hardware and the software required. We show its implementation in the robot Obrero [28], allowing it to safely reach, grab and replace objects that are delicate, whose properties are unknown, and that are not held in place by a fixture. Obrero can also make insertions by feeling the hole without a specialized mechanism, all of which are current limitations of traditional approaches. The use of tactile feedback allows the robot to effectively interact with objects to manipulate them. However, the general purpose manipulation requires knowledge of the context of the task to perform. For example, a hand tool like a hammer should be grabbed by its handle in order to use it effectively. The work presented in this paper address how to grab the handle based on interaction but does not address the context of the task.

2. Sensitive Manipulation

The main idea behind this approach is making contact with the object to manipulate as soon as possible and use the contact feedback to explore the object and control the physical interaction. This approach is inspired in human manipulation. Humans use a set of strategies collectively called *exploratory procedures* (EP) [2] in their perception of the world around them, such as tracing object, unsupported holding or enclosure.

If the robot is capable of coming in contact with an object gently and detect the interaction then the algorithm for manipulation can rely on tactile feedback. For example, if the robot needs to grab and object from a table, the robot can make the first contact to verify the object's presence, move its hand around the object to embrace the object with the robot's fingers while maintaining contact, grasp the object confirming that the fingers are making contact with the object, lift the object while detecting the grasp is stable, placed on a surface confirming that the object is supported.

The execution of these steps is reliable because if relies on contact feedback to control the physical interaction. For example, if the robot reaches for an object and it does not make contact it can take actions to search for the object or cancel the operation. In order to make this approach possible the robot's hardware needs to be considered. The robot's hand and arm needs to be capable of gently come in contact and the tactile sensors need a number of characteristics that include high sensitivity, normal and lateral force detection, and conformation. These two considerations are related because the robot need to be able to touch the object lightly to avoid moving it and that contact need to be detected. Once the contact is made the sensors should be able to detect the force vectors applied to the object while providing an adequate physical interface to interact with the object. Different aspects of the platform and the strategy of Sensitive Manipulation have been explored by a number of researchers as we describe along this paper. Sensitive Manipulation enables the integration of many of these components. We have implemented a platform with similar characteristic to the ones of human limbs and developed manipulation strategies using these characteristics. In the following sections we describe both the characteristics of the hardware required and the manipulation strategies.

2.1. *Strategy*

We consider that most of the relevant information for the tasks is extracted by interacting with the environment and reactively responding to it. We deliberately avoid to rely on an exact configuration of the robot's limb and a precise model of the surroundings.Therefore, the strategy consists in generating the interaction by executing explicit actions allowing the robot to deal with positioning error.

Two examples of this approach are: (1) a robot can confirm contact with the object to manipulate and position its hand around the object by reactively responding to the object's geometry, therefore not having to rely only on a kinematic model; (2) a robot can sense the physical interaction between its hand, the object held, and its surroundings to place the object on a surface, execute an insertion, or perform a stable grasp.

Implementing a task using this strategy increases, in general, the number of steps (subtasks) needed while increasing robustness and reliability (See Algorithm in Figure 9). Examples for specific tasks as described in the following sections.

2.1.1. *Pre-grasping*

In this strategy pre-grasping consists on making the first contact with the object to manipulate and repositioning the hand for grasping using tactile feedback. This first contact confirms the position of the hand with respect to the object so that errors can be consequently corrected with this information [29,23,24]. This first contact needs to be gentle to avoid knocking over the objects. In addition the sensors have to detect the contact independently of the geometry of the object and orientation of the finger. Conventional approaches attempt to grasp an object directly, without first coming in contact with it. In these cases reaching for the object is performed by moving the hand to a desired position and orientation with high precision and subsequently closing the hand. It requires that the object be in an exact position, pose, and, in many cases, a fixture. The grasp may fail due to noise or errors in the estimation of the object position or if the latter moves due to unexpected contact. A number of different remote sensors such as sonar, cameras, and laser scanners are used to estimate the pose and position of the object. The output of processing the sensors' feedback is a probability distribution of the pose and position. Using these estimates an open-loop grasp can be performed [30,31]. However, there is no confirmation that the object has been reached/touched and a fair amount of computation is needed. In some cases force sensing in the fingers' joints (load cells) or the surface (rigid tactile sensors) [13,29] are used to remove uncertainty. In general, however, these sensors do not have adequate characteristics since they are rigid and apply high forces to the object, detecting normal but not shear forces, or are only responsive to certain geometries. For instance, [29] reports that 25% of the contacts are not detected by the robot's sensor. New tactile sensing technologies are being developed [6,7,5] to give tactile sensors some of these properties. Another potential problem arises if the mechanical impedance of the finger is high and the latter moves the object upon contact unless it is heavy or anchored (like a door handle [23,24]), or the finger moves slowly. Because of these issues, this first-contact phase is avoided even in approaches based on tactile feedback [18]. The hand only makes contact with the object when two opposing fingers are carefully positioned [13]. However, when active contact sensing is used, even with high stiffness, it allows to adjust the position of the fingers for grasping [17]. In our approach we take advantage of the robot's sensing capabilities and moves the robotic arm until contact is detected (Active Sensing)[32]. The sensor's and hand's characteristics required for this subtask are described in Section 2.2. The contact confirms that the robot's arm has reached the object independently of the relative orientation of the hand and the part of the object touched. Coming into contact is safe because the tactile sensors are compliant and reduce the forces applied to the object. Contact detection is guaranteed since the sensors' response is independent of the local geometry of the object [33]. Finally, the robot can deal with uncertainty in the position of the hand or the object because on contact the object's position relative to the robot is known. The hand then can be reoriented and repositioned by feeling its way around the object until the fingers enclose the object. This method is independent of the object's shape (within a given range) and does not require a specific orientation of the hand.

2.1.2. *Grabbing an object*

In general, a hand configuration must be pre-determined for each object to grab using a criterion, such as force closure, that guarantees that the object will not fall. A open-loop grasp (i.e. without contact feedback) can be performed using this configuration [30,31]. Usually, it is not confirmed with tactile feedback that the object is enclosed by the fingers as a result of the planned moves. Moreover, the robot is not responsive to changes in the position of the object due to external forces. This can cause the grip to be lost or the object to be wrongly oriented for the task. Compliant hands solves some of the problems when the pre-grasp position is within an acceptable range [13]. However, contact active sensing, using load cells, improve grasping [17]. In our approach we rely on compliance using low-compliance actuators (Series Elastic Actuators [34]) and active force control [28]. In addition the robot uses tactile feedback to feel the presence of the object and adapt the hand to achieve a more reliable grasp. As a consequence we obtain the following behaviors for grabbing objects.

Maintaining contact The force exerted by the fingers, not their position, is controlled, making them responsive to changes in position and allowing them to stay in contact with the object.

Centering the object with respect to the hand Closing the fingers around an object can cause the relative position between the fingers and the object to change. These changes might leave them in a position less than ideal for grasping. Therefore, a behavior that centers the fingers respect to the hand helps to maintain a better grasp. This behavior uses the previous behavior (Maintaining contact) for centering the object.

Reducing stress using conformable skin In general, the model of a punctual force applied by a rigid fingertip is used to determine the grasp [35]. This punctual force will produce a large stress in an object that could damage it. In practice, this model is usually invalid because the rigid fingertip is covered by a soft material to improve the grasp and avoid damaging the object [15]. We use a conformable skin that can estimate directly the force distribution applied avoiding the punctual contact model. At the same time, the conformable interface distributes the forces applied, reducing the stress, and thus allowing the manipulation of brittle objects.

Confirming the presence of the object Detecting contact with an object using tactile sensors should be an straight forward tasks. Nevertheless, the tactile sensor has to be designed so that the detection is independent of the objects local geometry. In most cases tactile sensors can detect contact with sharp geometries but not with flat smooth ones [33]. It is also usual that the sensors are rigid and any motion will change their reading because it will lose contact. This limitation on the sensors is usually modeled as noise [29]. In this work, we consider sensors that do not have these limitations (Section 3.1).

2.1.3. *Placing and inserting an object*

Usually, placing an object on a surface consist of positioning the object just above the surface without contact, and then releasing it. There is no confirmation of the object touching the surface. This approach works well when the object is held at a specific predetermined point, the configuration of the arm is precisely achieved, and the surface's position is precisely known. Using this approach to perform insertions sometimes requires special mechanisms such as Remote Center of Compliance (RCC) [36] or strategies with compliant motion [16] to compensate for position errors and avoid jamming.

We build on compliant motion strategies [16] and rely on sensing of external forces to safely and robustly handle an object. The robot can move the object in its grasp towards the surface until it detects a change in the forces due to contact. This makes the robot robust to uncertainties in the model of the object, the coordinates of the surface, and the position of the fingers relative to the object. Moreover, it guarantees that the object is in contact with the surface before releasing it.

In the case of insertion, the change in the forces due to the contact between the object and the edge of the hole is detected and inherently compensates for positioning errors in a similar manner to a RCC mechanism or compliant motion strategies [16].

2.1.4. *Stable lifting of objects*

In general, it is assumed that the robot's fingers are in a configuration that guarantees a stable grasp. Therefore, no feedback is used during the lifting phase. We use tactile feedback along the motion of the object is used to detect if there is instability and compensate as needed.

2.2. ***Robotic hardware***

To show the feasibility of our approach we developed (1) compliant tactile sensors capable of reliably detecting the physical interaction while providing an adequate physical interface to handle objects and (2) compliant arms and fingers capable of gently interacting with the environment. These two changes allows to take advantages of the wealth of work on manipulation using tactile feedback and compliant motion.

2.2.1. *Compliant Tactile Sensors*

A number of different tactile sensing technologies have been developed [8]. Sensors have been created for spatial resolution [9], normal force fidelity [37], shear force detection [38,39], vibration [7], heat [7], compliance [7,6], and texture detection [40,9]. Many of these technology are still not mature to be employed on real robots (with some exceptions [41,19,42,43,44,45]). We consider that effective tactile sensors for robotic manipulation need the following characteristics. The importance of these properties for specific tasks will be covered in the following sections.

(1) Force detection. High sensitivity to normal and shear forces (a three dimensional vector) to give a complete estimation of the contact forces.
(2) Geometry independence. Responsive to local features that can be both pointed or flat.
(3) Compliance and saturation. Have low mechanical impedance to minimize the force applied upon contact and be capable of operating in saturation to handle forces that are out of range.
(4) Deformable. Conform to the object to reduce the stress applied.
(5) Compact. Easy to mount on actual robots in large quantities.
(6) Friction. Have a high friction coefficient with a number of materials to increase contact shear forces.

To meet all these requirements, we have invented a new tactile sensing technology [46,33] developed specifically for Sensitive Manipulation and inspired by the ridges and innervations of the human finger [47] (Figure 1).

2.2.2. *Compliant arms and fingers*

Industrial robot's structure and its control are designed to minimize the deflection that an external force can cause when applied to it. This feature, known as high impedance ($\sim 600,000 Nm/rad$), makes it difficult to come in contact safely with the environment because the high reactive forces can cause damages. In contrast, the human arm has low stiffness in static ($< 20 Nm/rad$) and dynamic cases ($< 40 Nm/rad$) [48], which makes possible a safe interaction with its surroundings. In robotics, compliant arms with force control capabilities have been developed for research laboratories and industry [10,28,11,49,50]. Series Elastic Actuators (SEAs) are a successful approach to implement these type of arms because they use passive elements (i.e. springs) in the driving mechanism. SEAs have been tested in legs [51,52], arms [10,28,11] and fingers [28]. Using SEA to drive each joint, we developed a fully compliant arm and fingers used for our approach.

3. Experimental Setup

3.1. *Tactile Sensor*

The sensor consists of a hollow hemi-spherical shape, made of silicone rubber, that deforms when stress is applied at any point (Figure 1A). The estimation of the force vector is achieved by detecting the position of the tip of the sensor using either optics or magnets [46,33]. In Obrero's sensors the position of a magnet embedded in the tip of the structure is estimated using a 2 by 2 square array of Hall effect sensors in the base of the structure. The normal force (Figure 1A2) is estimated by adding the outputs of the Hall effect sensors and the main components of the shear forces (Figure 1A3) by subtracting the outputs of the rows or columns respectively. The spherical shape of the sensor makes it likely that the first contact with an object is at a point only. The stress at that point will be high causing the deformation of the structure. This makes the sensor response independent of the objects geometry and the incidence angle. It also makes the sensor highly sensitive. The three components of a force applied can estimate based on the structure deformation. The sensor also conforms to an object to reduce stress, has a high friction coefficient because of its constituent material, and can be saturated (flattened) without losing its functionality. It is compact and easy to fabricate in large quantities using standard molding techniques. Examples of the sensitivity of these sensors can be seen in movies S1, S2, S3, and their conformation capability in movie S8. A detailed analysis of the sensor response and its properties is in [33].

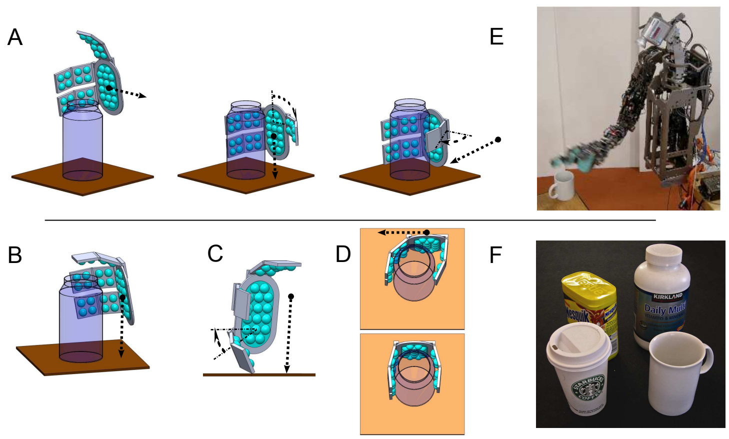

Fig. 2. **(A)** The low impedance and compliant tactile sensors allow the hand to approach an object from its side, without it being in a fixture, or knowing the angle of incidence with respect to the sensors. The hand explores the space until the fingers touch the object. The approach is made by the side with the arm sweeping first sideways and later downwards. This exploration continues until contact with the fingers is achieved. If only the middle finger has made contact, the hand moves downward until the index finger makes contact. The thumb then rotates to oppose the index finger. The hand moves forward in the direction of the forearm and on contact with the palm, the fingers and thumb close. If during the downwards arm motion the hand comes into contact with the table, the motion is corrected S4. **(B)** The approach can also be performed from above. The thumb bends forward to make contact with the object. This approach is particularly useful when the mass of the object is low S5. **(C)** The contact detection with the table, or other surface, can be done by reading the angular change of the middle finger that safely gives in upon contact because of the series elastic actuator in its joint. The finger is positioned to increase its chance of first contact. **(D)** When closing the thumb to grab an object as described in A and B, the most expected outcome is that the fingers are not symmetrically distributed with respect to the object. Therefore, the wrist moves to achieve alignment. The force applied by each finger, and not its position, is controlled while the wrist moves. **(E)** Obrero approaching an object from its side. **(F)** Objects used in the experiments: a plastic bottle, a porcelain cup, a plastic cup and a rectangular plastic box. Some objects were partially filled to increase weight (all objects weighed approximately 220-265 g)

3.2. *The humanoid robot Obrero*

For our experiments we developed the robot Obrero [28] (Figure 1), which has a torso, head, arm, and hand. The robot's arm has three degrees of freedom (DOF) on the shoulder, one on the elbow, and one on the wrist. All DOFs are driven by series elastic actuators (SEA) [34] making the arm compliant. The hand has two fingers (index and middle) and a thumb each with two coupled DOFs (Figure 1C). The thumb and middle finger can rotate with respect to the palm (Figure 1B). The fingers and thumb have two levels of compliance, first from the miniaturized SEAs on their joints, and second from the deformable tactile sensors (Figure 1D and 1A). This compliance makes it possible to come in contact with the environment gently, while not limiting the force that can be applied.

3.3. *Objects*

We choose objects (Figure 2F) that are difficult to manipulate because they have a high center of gravity, are slippery on the table, and have a small mass $(220-265g)$. At the first contact with a robot hand, these objects will be knocked over or pushed. Moreover, they represent a challenge for tactile sensors because of the following factors. Their bodies have low curvature with reduces the stress and make difficult to deform a sensor to allow detection. It is easier to detect the objects edges because the stress on a sensor can be increased with a given force. Most technologies will not detect the contact because the force applied by one finger on an object will move the object losing the contact. Low mechanical impedance is needed on the sensors and the fingers to detect interaction forces. Shear forces are not easy to detect in these objects because of their lack of texture. However, these objects are easy to manipulate for human and we chose them to demonstrate the capabilities of the robot and our approach.

4. Methods and Results

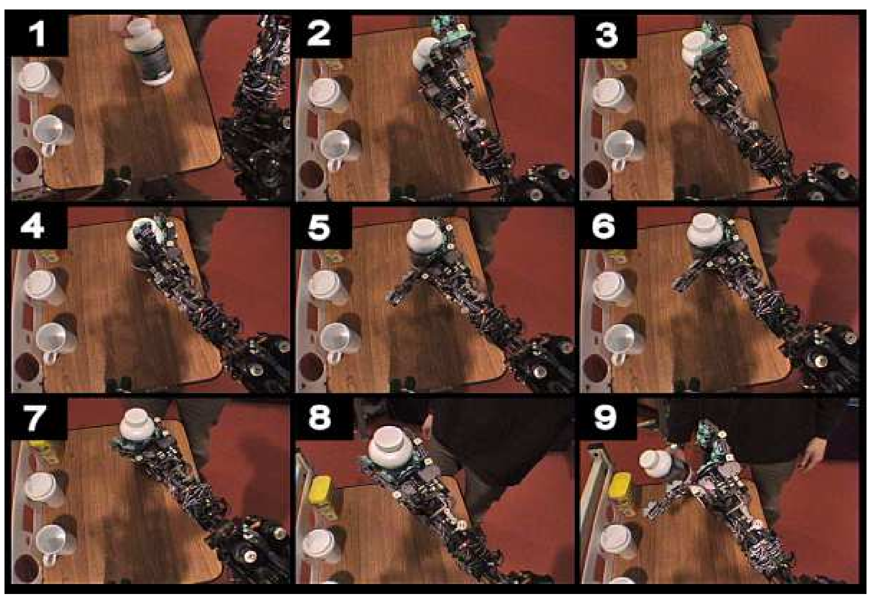

Fig. 3. Grasping sequence from the robot's point of view: an example. Frame 1: An object is waived in front of the robot to attract its attention. Frame 2: The robot detects the motion and moves the hand towards it. This is the only part of the sequence where visual information is actually used. At this point the robot starts exploring the space around the area where motion was detected, until the fingers and the palm touch the object (frames 3 to 6). Frames 7 to 8: the robot grasps the object and lifts it. Frame 9: the robot releases the object.

Our approach was demonstrated in the following tasks.

4.1. *Pre-grasping steps to eliminate uncertainty with an unknown object*

The goal of this task is to leave the hand in a position ready to grasp. The pre-grasping task is divided into 1) locating the object and 2) positioning the hand for grasping using touch.

4.1.1. *Locating an object using touch*

After roughly estimating the position of the object using vision, the arm moves until it touches the object. The contact, confirmed using tactile sensors, indicates that the object has been located. This removes the uncertainty about the position of the object relative to the robot.

If no contact is detected, the robot can explore the environment searching for the object using touch. This drastically reduces the dependence on the precision of the model of the environment, as in traditional methods, since the robot can safely explore its environment. It is important to note that this strategy relies on an effective detection of contact requiring tactile sensors that work independently of the angle of incidence and the local geometry of the object. This requirement led to the design of the sensors described previously in section 3.1.

This approach was implemented in Obrero (see movie S4). The robot is positioned in front of a table with its arm above the surface. When a person waves an object on the table, Obrero moves its hand towards the object roughly estimating its position using the motion detected, the kinematics from the head and the arm, and the table's height. The table's height is previously estimated by coming in contact with it (Figure 2D). The trajectory used for this experiment approaches the object from the side with the hand configured as shown in Figure 2A. The thumb is up to allow the inside of the hand to come into contact with the object, which is convenient for grasping it.

No visual feedback is used during the approaching stage to show the effectiveness of the strategy. If no contact is detected, an exploration around this position is performed. The hand moves to the side and to the front parallel to the table. These directions are computed using the kinematics of the arm. If contact is detected, the exploration stops, because the object has been located with no position uncertainty. The first contact behavior is also shown in Figure 4.

4.1.2. *Positioning hand for grasping*

After the first contact with the object, the hand is moved to a position and configuration favorable for grasping. The position and configuration are specific to the task. For instance the configuration for grabbing with fingertips is different from the one with fingers and palm (power grasp). In traditional methods, this task is not needed because it is assumed that the hand reaches precisely the ideal position for grasping according to a given model.

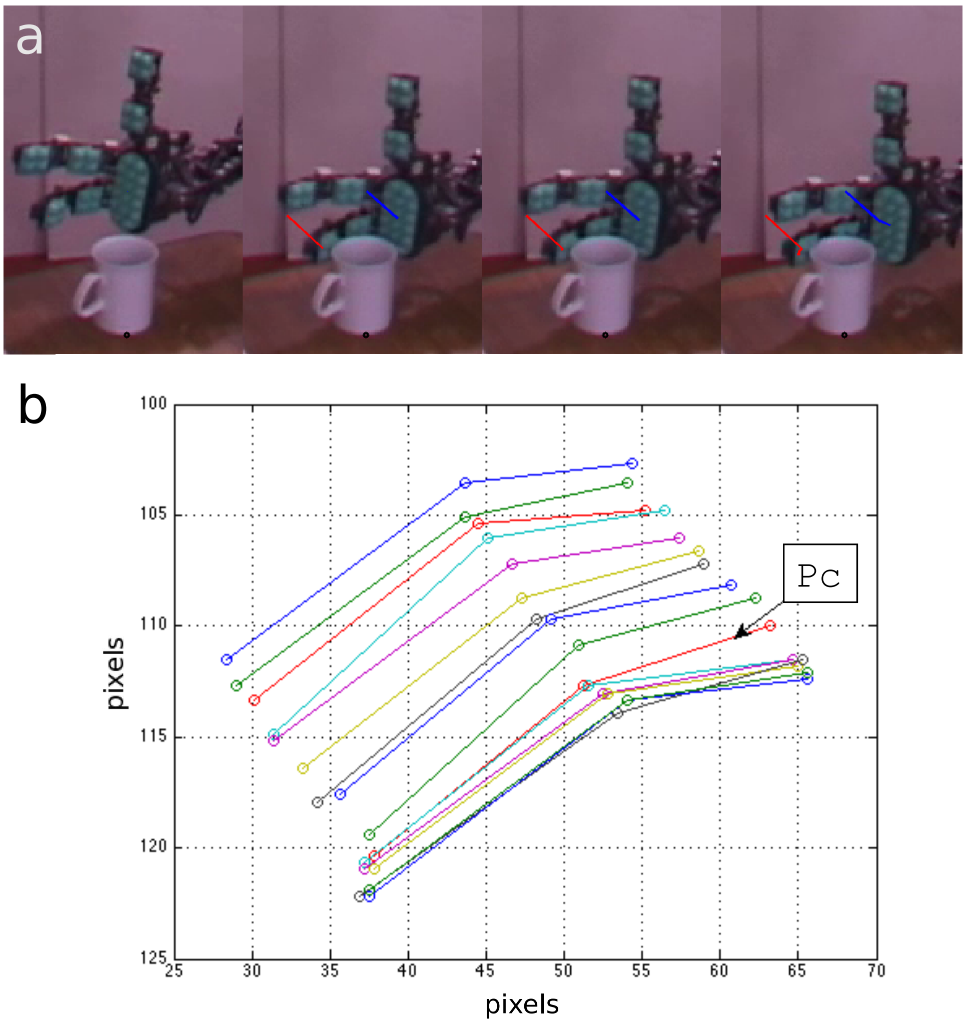

Fig. 4. First contact. (a) The hand moves to make the first contact. It is expected that the object (cup) will not be knocked over because of the finger's low mechanical impedance (high compliance). The trajectory of the lowest fingertip, the center of the palm, and the base of the the cup are tracked in the images. In this case the cup did not move when came in contact with the hand. (b) Shows the positions of the index finger phalanges' on the image. The phalanges' position are visually tracked as the hand moves down towards the object. After the lowest finger makes contact with the object (event marked by point Pc) it can be observed that the angle between phalanges changes because of the compliance.

For this example, we had Obrero's hand approaching the objects from the side to perform a power grasp (Figure 2A). If only the middle finger came into contact, it retracts a small angle (5°). The hand moves to the side and then down until the index finger comes in contact with the object. The thumb then rotates to the same plane as the index finger. If there is no contact with the palm, the hand moves in the direction of the forearm until contact occurs. The hand is now ready to grasp the object. The sequence can be observed in Figure 3 frames 1 to 6.

The strategy described above can use different approaching trajectories or exploration patterns. In general, the choice depends on factors such as the object's properties or task to be performed. For instance, the side trajectory is appropriate to grab a cup of coffee, however, if the object is lighter or taller it is likely to knock it over. In that case approaching the object from above, with the hand configured as in Figure 2B, would be a better strategy. This is shown in movie S5.

Sensitive Manipulation takes advantage of the compliance of the robotic fingers, their force control and the conformability of the tactile sensors. Therefore, once the hand has been positioned (Figure 3 frame 6) the strategy is simply close the hand of the robot using force control until additional contact with the object is detected. The hand can be moved to improve the grasp or compensate for external forces while maintaining contact.

4.1.3. *Confirming the presence of the object*

The contact with all the objects was detected independently of the local geometry of the object. In some cases, parts of the objects touched areas not covered with tactile sensors, like the joints, and these specific contacts were not detected. However, the object also touched other parts of the fingers that allow to detect the presence of the object.

4.2. *Grasping an object without information about it.*

After the robot has positioned the hand around the object and the following behaviors are used.

4.2.1. *Maintaining contact*

Obrero's hand controls the force exerted by the fingers instead of their position. Therefore, if the object or the hand moves, the fingers maintain contact with the object, within some range, giving a better grip. This is shown in movie S6 and Figure 5.

4.2.2. *Centering the object with respect to the hand*

When the fingers close, they may end up in an asymmetric position with respect to the palm (Figure 2D). To achieve a symmetric position Obrero moves its wrist while applying more force with the finger that is more open until the angles of the proximal phalanges differs less than 5°. This centering behavior is shown in movie S7.

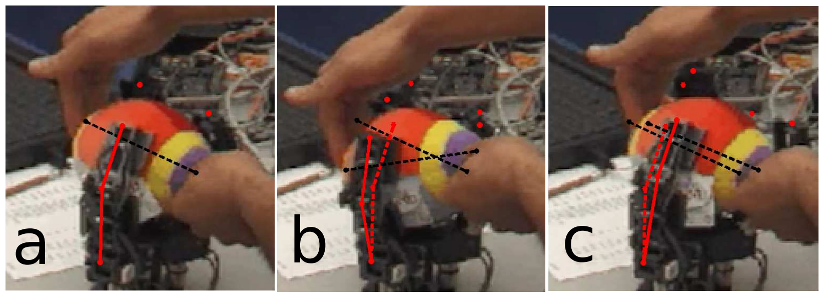

Fig. 5. Maintaining Contact behavior. As the football is moved the fingers react and maintain contact using force control. (a) Original position of the football when grasped. (b) and (c) show the changes of the fingers' position with respect to (a) as the football moves.

4.2.3. *Distributing stress*

The compliance of the tactile sensors allows them to conform to the object's surface thus reducing the local stress and decreasing the chances of damaging the object. This compliance is shown in movie S8 and in Figure 7. In Figure 7 a transparent glass is used to easily observe how the sensors conform to the shape of the object. This conformation reduces the stress on the surface enabling grasping objects as brittle as the glass or an egg.

4.3. ***Stable lifting***

Obrero is capable of detecting changes in the interaction force to estimate the stability of the grasp, which contrasts with traditional methods that use a pre-computed hand configuration that meets the criteria of form or force closure.

This strategy is inspired by human manipulation where the slippage is detected by the Meissner's corpuscles that pick up the oscillations generated when a moving object "catches and releases" our skin.

Obrero's four sensors per tip (compared to about 300 per square centimeter in humans [53]) are not enough to measure the "catch and release" effect in time to increase the force applied. Instead, Obrero measures the change of the lifting forces, allows the object to rest again on the surface and then retries the lift applying greater force.

The behavior of the forces measured by the tactile sensors are similar to the ones obtained by direct measurement in tactile innervations in humans [3]. This implementation can be observed in movie S11.

Obrero lifts a cylindrical bottle of unknown size and weight in two attempts. In the first one, the bottle slips and in the second one the bottle is held steadily. The dimension of the bottle are $mass = 0.179\,Kg, diameter = 92\,mm, height = 216\,mm$ but the robot has no knowledge of them. The robot approaches the bottle from the side (as shown in figure 2A), on contact the thumb is rotated to oppose the index finger. Next, the thumb and index finger are closed gently until contact with

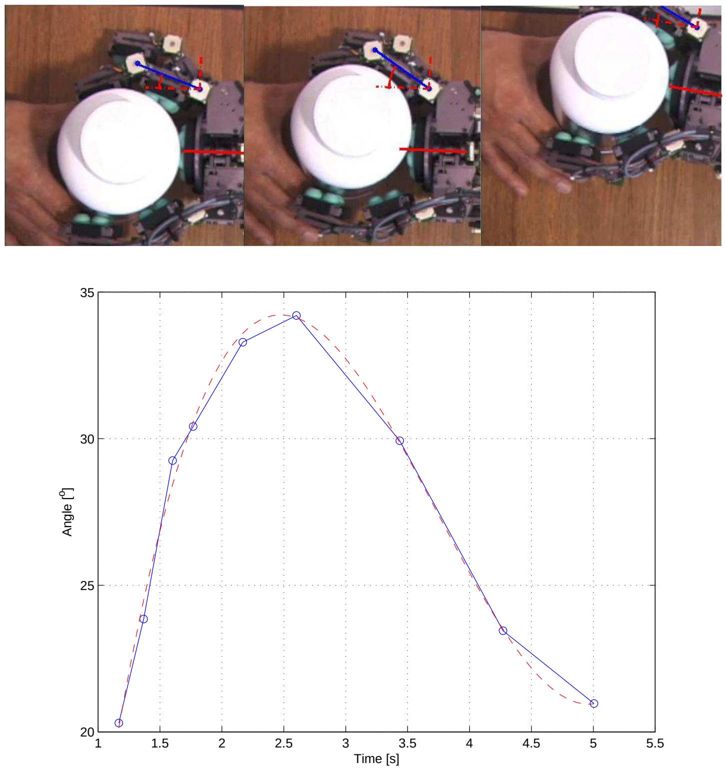

Fig. 6. Hand centering behavior. As the bottle is moved, the finger are moved and are not positioned symmetrically respect to the wrist. Contact is maintained because of the force control. The wrist moves to position the fingers symmetrically respect to the center of the wrist. The finger's angle is shown in the plot. The blue segments represent the data collected while the red line is a 4th order polynomial fitted to the data.

the object is detected. Figure 8E shows the configuration of the hand, the angles measured, and the shear (${}^{i}w$ and ${}^{i}f_{s1}$) and normal (${}^{i}f_n$) forces estimated by the sensors. Figure 8F shows the force response during the lifting of the bottle. In the first attempt the object slips (F_T goes to zero between T_1 and T_2). Obrero releases the object and on the second attempt applies more force and lifts the object (F_T remains at the weight of the object between T_6 and T_7).

4.4. *Placing objects on surfaces and performing insertions*

Sensitive Manipulation can place an object on a surface with a more reliable and flexible strategy by detecting the lateral and normal forces of the object being held (Figures 8A and 8B). This strategy also applies to tasks such as handing an object to a person.

To do this, Sensitive Manipulation moves the robotic arm towards the table

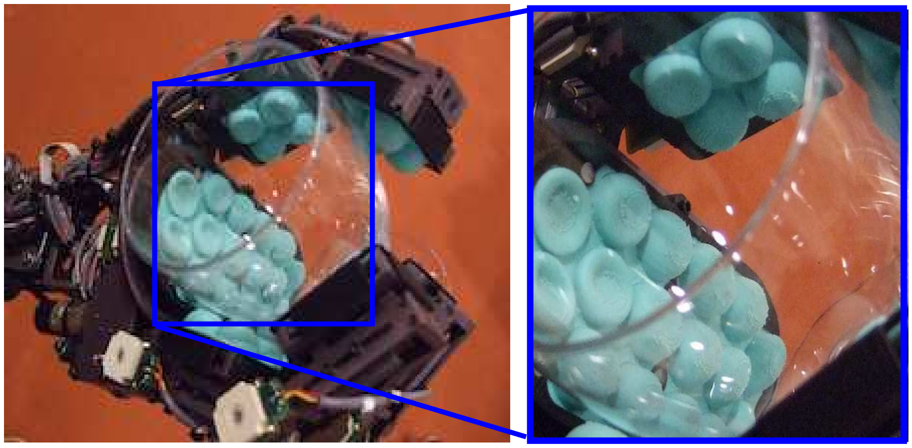

Fig. 7. Close-up view of the hand holding a glass. The sensors conform to the object reducing the stress. The compliance of the fingers, under force control, makes possible that the fingers remain in contact with the glass when grasping

(Figure 8C) until the contact is determined by measuring the force applied to the object by the table (Fc). This compensates for imprecision in the table coordinates, is independent of how the object is held, and confirms that the surface was touched before releasing the object. This strategy is shown in movie S9where the robot releases a bottle when a person places his hand under it.

Insertion is another task that is approached with a more flexible strategy by detecting the interaction forces. Obrero starts by bringing the parts in contact and then explores to detect the insertion location (Figure 8D). The robot first moves its hand down to detect contact (Figure 8C). On contact, the hand moves across the surface until a change of forces (Fr) occurs when the bottle fits in the hole. At this point, the bottle is released. This example is shown in the movie S10.

4.5. *Grasping Results*

The steps previously described were integrated to evaluate the grasping as a simple behavior. In this experiment, we presented different objects to the robot and counted the number of successful grasps. We chose objects of different sizes and shapes: a round plastic bottle, a rectangular plastic box, a porcelain cup, and a plastic cup (Figure 2F). Some of the objects were partially filled, so that the weight was roughly uniform among all objects (220-265 grams). The robot had no prior information about these objects. Each object was presented to the robot at least 20 times and randomly placed on the table. 87 of 94 trials (93%) were successful. InB the unsuccessful cases, the exploration was aborted because there was no contact with the object.

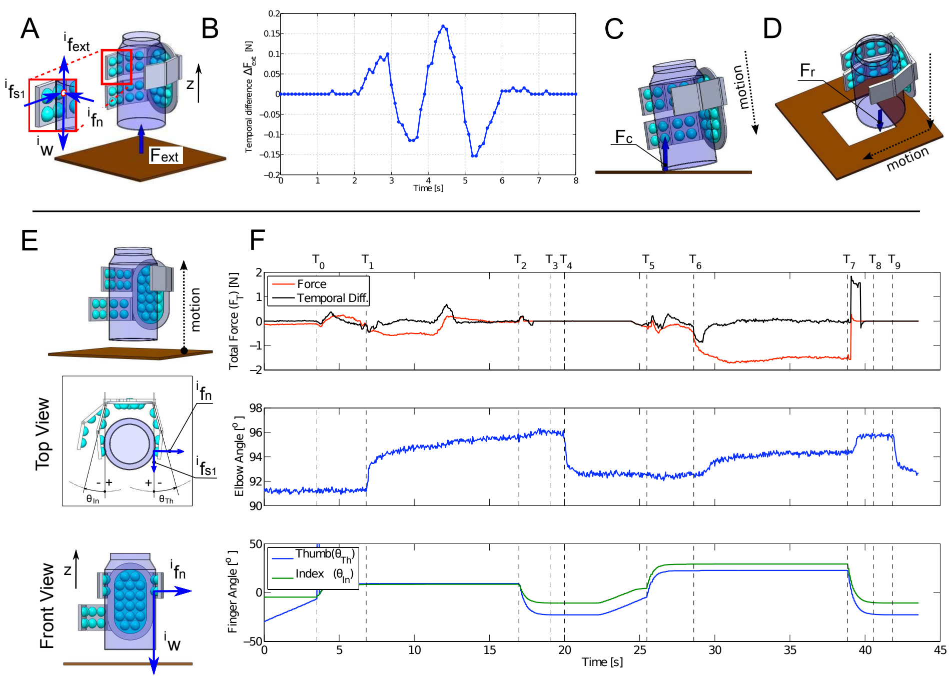

Fig. 8. Normal and Shear Forces. **(A)** Detail of the i-th sensor response when an object is held by the hand. The normal force ${}^{i}f_n$ is applied by the finger against the object. The shear force ${}^{i}w$ is exerted by the object's weight. The shear force ${}^{i}f_{s1}$ is exerted by either the weight if the bottle is not held vertical or by the local geometry of the object. In this case, we assume ${}^{i}f_{s1} = 0$. The shear force ${}^{i}f_{ext}$ is the response of the sensor i to the force F_{ext} applied to the base of the bottle. **(B)** To show that the robot can detect forces applied to an object that is being held, F_{ext} was applied by tapping twice the base of the bottle. The plot shows the temporal difference of the summation of shear forces of all the sensors on the Z-direction. $\Delta F_{ext} = F_{ext}(t) - F_{ext}(t - T)$; where $F_{ext} = \sum_i {}^{i}f_{ext}$ for all sensors. The values showed have been filtered using a moving average filter of size 8 and the sampling period of 100ms. **(C)** To place the bottle on the table, the robot moves the bottle until it comes in contact when it is released. The contact is detected by the changes on the shear forces as in (B). **(D)** The insertion of the bottle is done by first moving the bottle downwards to detect the contact with the table and later moving the bottle on the table until the shear forces change because the bottle gets in the hole. **(E)** Angles and forces considered. Θ_{In} and Θ_{Th} are angles of the Index finger and Thumb. ${}^{i}f_n, {}^{i}w$, and ${}^{i}f_{s1}$ are the force component estimated by the sensor. The sensor responds to the local geometry of the object as well as external forces. **(F)** The summation of all the sensors on the Z-direction, $F_T = \sum_i {}^{i}w$, is used to analyze the lifting of the bottle. The response to the local geometry of the objects can be observed between the times T_0 and T_1 . The hand starts moving upwards at T_1, which is indicated by the increment of Elbow Angle. Between T_1 and T_2, we observe that F_T decreases because of the weight of the bottle but later goes back to zero. This shows that the hand lost contact with the bottle because it slipped. Consequently, the robot retries the lifting. The fingers are opened at T_2 and the elbow goes back at T_4. The fingers are closed more than previously at T_5 because of the greater force applied. Between T_5 and T_6, we observe the response of the sensors due to the local geometry of the object. Between T_6 and T_7, F_T reaches a stable value that closely correspond to the weight of the bottle. This force changes at T_7 when the fingers are opened. The temporal difference of F_T ($\Delta F_T = F_T(t) - F_T(t - T)$) is used to detect slippage. Between points T_1 and T_2 there is a large positive slope while the fingers are closed, which corresponds to the loss of contact with the bottle. Between points T_6 and T_7 there is a slight slip that stops and the grasp stabilizes.

Algorithm to grab an object using tactile feedback

```
▷/ *** Pre-grasping stage ***/
LocatingObject(); ▷ Move hand until touch is detected
while ( ObjectIsNotInsideTheHand() ) ▷/* Is the object touching the palm and fingers? */
    PositioningHand(); ▷/* Move hand around object while making contact */

▷/ *** Grabbing stage ***/
CloseHand(); ▷/* Close fingers in force control mode until force threshold is reached */
CenteringWrist(); ▷/* Center the object on the hand respect to the wrist */

▷/ *** Lifting-and-Moving stage ***/
while ( IsLiftingStable() and ▷/* Do forces in the direction of motion change? */
        not( MotionCompleted() ) ) ▷/* Completed motion? */
    MoveArm(); ▷/* Continue moving towards the surface */
if not ( IsLiftingStable() ) Cancel(); ▷/* Was the motion stable? */

▷/ *** Placing-Object-on-Surface stage ***/
while ( NoContactWithSurface() ) ▷/* Do forces in the direction of motion change? */
    MoveArmTowardSurface(); ▷/* Continue moving towards the surface */
OpenHand(); ▷/* Open fingers until no contact is detected */
```

Fig. 9. Overall algorithm to grab, lift, move, a replace and object. An explanation of the procedures can be found in Section 4.

5. Conclusions and Future work

In this paper we show an approach to robotic manipulation that relies on compliance, tactile feedback and explorative behaviors. We showed that following this approach allows the robot Obrero to perform a variety of different tasks in an unstructured environment. The main idea is coming in contact with the environment as soon as possible and exploit the information generated by the interaction to guide the exploration and consequent actions. Thanks to a careful design of the hardware and control strategies the robot can come in contact with the environment safely, sense the interaction forces, and perform tasks using this information. One of the key elements of our approach was the development of a new biomimetic tactile sensors that extract information relevant for the tasks to perform and provide a compliant surface interaction, similar to a human skin. We demonstrate our approach using

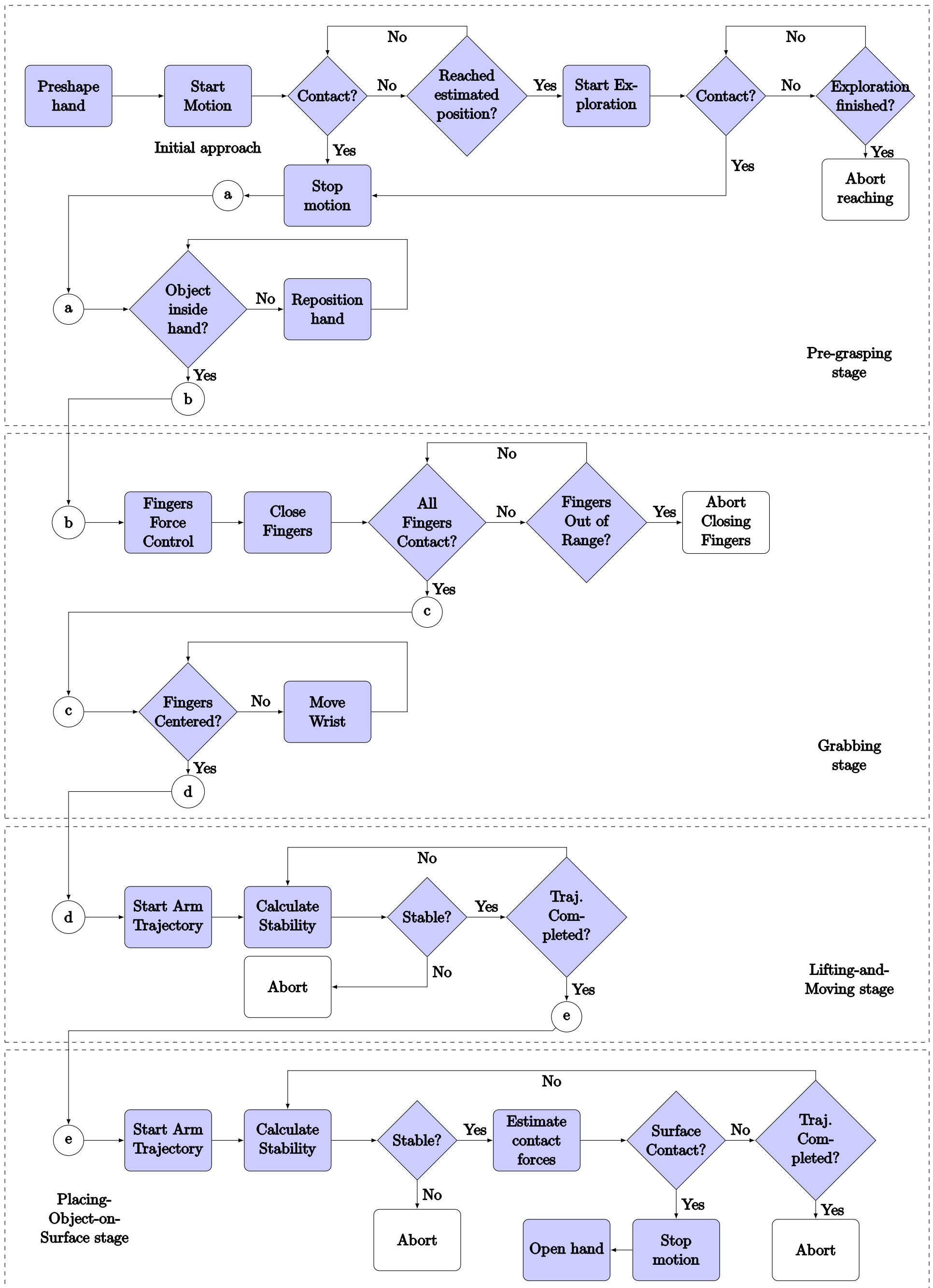

Fig. 10. Flow chart of the algorithm to grab, lift, move, a replace and object. An explanation of the procedures can be found in Section 4 as well as in Figure 9. The names of the stages and methods (separated by labeled circles) correspond to ones described in Figure 9.

the robot Obrero, showing that it can execute tasks without previous knowledge on the position, size or weight of the object, the surface on which it rests, or the hole for insertion. These tasks include: approaching an object, positioning the hand around it, grabbing the object after centering the fingers around it, placing the object on a table, lifting the object from the table, and performing insertions.

Given the size of the fingers we focused on object manipulation using full hand grasp (i.e. power grasp). Although not demonstrated here our strategy can be applied to object parts and extended to cover more general cases (i.e. grasping an object by the handle or a tool or small slippery parts [54]). We hope that this paper will stimulate more work in this direction.

This means that Sensitive Manipulation does not require a detailed model for each object to be manipulated, is adaptive to the changes in the environment, and will not damage the object with which it interacts.

Acknowledgements

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Supporting Online Material

Movies S1 to S11

`http://people.csail.mit.edu/etorresj/`
`_VideosSensitiveManipulation/`

References

1. R. S. Johansson and G. Westling, "Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects," *Experimental Brain Research*, vol. 56, pp. 550–564, 1984, 10.1007/BF00237997. [Online]. Available: *http://dx.doi.org/10.1007/BF00237997*
2. *S. J. Lederman and R. L. Klatzky, "Hand movements: A window into haptic object recognition,"* Cognitive Psychology*, vol. 19, no. 3, pp. 342 – 368, 1987. [Online]. Available: http://www.sciencedirect.com/science/article/pii/0010028587900089*
3. *R. S. Johansson and J. R. Flanagan, "Coding and use of tactile signals from the fingertips in object manipulation tasks,"* Nat Rev Neurosci*, vol. 10, no. 5, pp. 345–359, 05 2009/05//print. [Online]. Available: http://dx.doi.org/10.1038/nrn2621*
4. *R. S. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing – from humans to humanoids," in* IEEE Transactions on Robotics*, vol. 26, 2010, pp. 1 – 20.*
5. *Roboskin. Roboskin project. [Online]. Available: http://www.roboskin.eu/index.php*
6. *Y. Tenzer, L. Jentoft, and R. Howe, "The feel of mems barometers: Inexpensive and easily customized tactile array sensors,"* Robotics Automation Magazine, IEEE*, vol. 21, no. 3, pp. 89–95, Sept 2014.*
7. *J. Fishel and G. Loeb, "Sensing tactile microvibrations with the biotac - comparison with human sensitivity," in* Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS EMBS International Conference on*, June 2012, pp. 1122–1127.*

8. *M. Cutkosky, R. Howe, and P. W.R., "Force and tactile sensors," in* Springer handbook of robotics*, B. Siciliano and O. Khatib, Eds. Springer, 2008, pp. 455–476.*
9. *M. Johnson and E. Adelson, "Retrographic sensing for the measurement of surface texture and shape," in* Computer Vision and Pattern Recognition, 2009. CVPR 2009. IEEE Conference on*, June 2009, pp. 1070–1077.*
10. *R. R. Inc. (2014) Baxter robot. [Online]. Available: http://www.rethinkrobotics.com/products/baxter/*
11. *A. Edsinger-Gonzales and J. Weber, "Domo: a force sensing humanoid robot for manipulation research," in* Humanoid Robots, 2004 4th IEEE/RAS International Conference on*, vol. 1, nov. 2004, pp. 273 – 291 Vol. 1.*
12. *G. Hirzinger, A. Albu-Schaffer, M. Hahnle, I. Schaefer, and N. Sporer, "On a new generation of torque controlled light-weight robots," in* Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*, vol. 4, 2001, pp. 3356 – 3363.*
13. *A. Dollar, L. Jentoft, J. Gao, and R. Howe, "Contact sensing and grasping performance of compliant hands,"* Autonomous Robots*, vol. 28, pp. 65–75, 2010, 10.1007/s10514-009-9144-9. [Online]. Available: http://dx.doi.org/10.1007/s10514-009-9144-9*
14. *E. Brown, N. Rodenberg, J. Amend, A. Mozeika, E. Steltz, M. R. Zakin, H. Lipson, and H. M. Jaeger, "Universal robotic gripper based on the jamming of granular material,"* Proceedings of the National Academy of Sciences*, vol. 107, no. 44, pp. 18 809–18 814, 2010. [Online]. Available: http://www.pnas.org/content/107/44/18809.abstract*
15. *A. M. Annaswamy and M. A. Srinivasan, "The role of compliant fingerpads in grasping and manipulation: Identification and control," Research Laboratory of Electronics, Massachusetts Institute of Technology, Touch Lab. Technical Report 603, January 1997. [Online]. Available: http://hdl.handle.net/1721.1/4151*
16. *T. Lozano-Pérez, M. T. Mason, and R. H. Taylor, "Automatic synthesis of fine-motion strategies for robots,"* The International Journal of Robotics Research*, vol. 3, no. 1, pp. 3–24, 1984.*
17. *R. Platt, A. Fagg, and R. Grupen, "Null-space grasp control: Theory and experiments,"* Robotics, IEEE Transactions on*, vol. 26, no. 2, pp. 282–295, April 2010.*
18. *J. M. Romano, K. Hsiao, G. Niemeyer, S. Chitta, and K. J. Kuchenbecker, "Human-inspired robotic grasp control with tactile sensing,"* IEEE Transactions on Robotics*, vol. 27, no. 6, pp. 1067 – 1079, December 2011.*
19. *R. Li, R. Platt, W. Yuan, A. ten Pas, N. Roscup, M. Srinivasan, and E. Adelson, "Localization and manipulation of small parts using gelsight tactile sensing," in* IEEE Int'l Conf. on Intelligent Robot Systems (IROS)*, 2014.*
20. *R. S. Dahiya, G. Metta, G. Cannata, and M. Valle, "Guest editorial special issue on robotic sense of touch,"* Robotics, IEEE Transactions on*, vol. 27, no. 3, pp. 385–388, June 2011.*
21. *U. Martinez-Hernandez, T. Dodd, L. Natale, G. Metta, T. Prescott, and N. Lepora, "Active contour following to explore object shape with robot touch," in* World Haptics Conference (WHC), 2013*, April 2013, pp. 341–346.*
22. *T. Bhattacharjee, J. Rehg, and C. Kemp, "Haptic classification and recognition of objects using a tactile sensing forearm," in* Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, Oct 2012, pp. 4090–4097.*
23. *P. Hebert, T. Howard, N. Hudson, J. Ma, and J. Burdick, "The next best touch for model-based localization," in* Robotics and Automation (ICRA), 2013 IEEE International Conference on*, May 2013, pp. 99–106.*
24. *S. Javdani, M. Klingensmith, J. Bagnell, N. Pollard, and S. Srinivasa, "Efficient*

touch based localization through submodularity," in Robotics and Automation (ICRA), 2013 IEEE International Conference on*, May 2013, pp. 1828–1835.*

25. *S. R. Soekadar, M. Witkowski, C. Gómez, E. Opisso, J. Medina, M. Cortese, M. Cempini, M. C. Carrozza, L. G. Cohen, N. Birbaumer, and N. Vitiello. Hybrid eeg/eog-based brain/neural hand exoskeleton restores fully independent daily living activities after quadriplegia.* Science Robotics*, 1(1), 2016.*
26. *D. Cafolla and G. Carbone, "A Study of Feasibility of a Human Finger Exoskeleton," in* Service Orientation in Holonic and Multi-Agent Manufacturing and Robotics*, , Borangiu T., Trentesaux D., Thomas A. (eds), Studies in Computational Intelligence, Springer, vol. 544, pp. 355-364.*
27. *E. Torres-Jara, "Sensitive manipulation," Ph.D. dissertation, Massachusetts Institute of Technology Computer Science and Artificial Intelligence Laboratory, 32 Vassar Street, Cambridge, MA 02139, 2007.*
28. *——, "Obrero: a platform for sensitive manipulation," in* Humanoid Robots, 2005 5th IEEE-RAS International Conference on*, Dec 2005, pp. 327–332.*
29. *K. Hsiao., "Relatively robust grasping," Ph.D. dissertation, MIT, 32 Vassar St. Cambridge, MA 02319, USA, 2009.*
30. *D. Berenson, S. Srinivasa, and J. Kuffner, "Addressing pose uncertainty in manipulation planning using task space regions," in* IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '09)*, October 2009.*
31. *M. Dogar and S. Srinivasa, "Push-grasping with dexterous hands: Mechanics and a method," in* Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, Oct 2010, pp. 2123–2130.*
32. *L. Natale and E. Torres-Jara, "A sensitive approach to grasping," in* Sixth international workshop on Epigenetic Robotics*, Paris, France, September 2006.*
33. *S. Youssefian, N. Rahbar, and E. Torres-Jara, "Contact behavior of soft spherical tactile sensors,"* Sensors Journal, IEEE*, vol. 14, no. 5, pp. 1435–1442, May 2014.*
34. *G. Pratt and M. Williamson, "Series elastic actuators," in* Intelligent Robots and Systems 95. 'Human Robot Interaction and Cooperative Robots', Proceedings. 1995 IEEE/RSJ International Conference on*, vol. 1, aug 1995, pp. 399 –406 vol.1.*
35. *Springer,* Handbook of Robotics*, B. Siciliano and O. Khatib, Eds. Springer, 2008.*
36. *D. Whitney, "When people are too large and dirty [manufacturing computer control],"* Spectrum, IEEE*, vol. 30, no. 9, pp. 39 –42, sep 1993.*
37. *V. Maheshwari and R. F. Saraf, "High-resolution thin-film device to sense texture by touch,"* Science*, vol. 312, no. 5779, pp. 1501–1504, 2006. [Online]. Available: http://www.sciencemag.org/cgi/content/abstract/312/5779/1501*
38. *K. Noda, K. Hoshino, K. Matsumoto, and I. Shimoyama, "A shear stress sensor for tactile sensing with the piezoresistive cantilever standing in elastic material,"* Sensors and Actuators A: Physical*, vol. 127, no. 2, pp. 295 – 301, 2006. [Online]. Available: http://www.sciencedirect.com/science/article/B6THG-4HDX6P8-4/2/47ab623290ef434f5e8f1c592e854a85*
39. *K. Noda, K. Matsumoto, and I. Shimoyama, "Tactile sensor with standing piezoresistive cantilevers, covered with 2-layer skin type structures for texture detection of object surface," in* Intelligent Robots and Systems, 2008. IEEE/RSJ International Conference on*, 22-26 2008, pp. 3953 –3958.*
40. *J. Scheibert, S. Leurent, A. Prevost, and G. Debregeas, "The Role of Fingerprints in the Coding of Tactile Information Probed with a Biomimetic Sensor,"* Science*, vol. 323, no. 5920, pp. 1503–1506, 2009. [Online]. Available: http://www.sciencemag.org/cgi/content/abstract/323/5920/1503*
41. *R. Pratt, F. Permenter, and J. Pfeiffer, "Inferring hand-object configuration directly*

from tactile data," *in* Electronically published proceeding of the Mobile Manipulation Workshop, IEEE Conference on Robotics and Automation (ICRA), *May 2010.*

42. *L. SynTouch, "Syntouch," May 2015. [Online]. Available: http://www.syntouchllc.com/Products/BioTac*
43. *P. Maiolino, M. Maggiali, G. Cannata, G. Metta, and L. Natale, "A flexible and robust large scale capacitive tactile system for robots,"* Sensors Journal, IEEE, *vol. 13, no. 10, pp. 3910–3917, Oct 2013.*
44. *H. Iwata and S. Sugano, "Design of human symbiotic robot twendy-one," in* Robotics and Automation, 2009. ICRA '09. IEEE International Conference on, *May 2009, pp. 580–586.*
45. *T. Asfour, K. Regenstein, P. Azad, J. Schroder, A. Bierbaum, N. Vahrenkamp, and R. Dillmann, "Armar-iii: An integrated humanoid platform for sensory-motor control," in* Humanoid Robots, 2006 6th IEEE-RAS International Conference on, *Dec 2006, pp. 169–175.*
46. *E. Torres-Jara, I. Vasilescu, and R. Coral, "A soft touch: Compliant tactile sensors for sensitive manipulation," MIT-CSAIL, 32 Vassar St. Cambridge, MA 02319, USA, Tech. Rep. MIT-CSAIL-TR-2006-014, March 2006. [Online]. Available: http://hdl.handle.net/1721.1/31220*
47. *G. Gerling and G. Thomas, "The effect of fingertip microstructures on tactile edge perception," in* Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint, *March 2005, pp. 63 – 72.*
48. *H. Gomi and M. Kawato, "Human arm stiffness and equilibrium-point trajectory during multi-joint movement,"* Biological Cybernetics, *vol. 76, pp. pages = 163–171, 163–171, 1997. [Online]. Available: http://dx.doi.org/10.1007/s004220050329*
49. *G. Hirzinger, A. Albu-Schaffer, M. Hahnle, I. Schaefer, and N. Sporer, "On a new generation of torque controlled light-weight robots," in* Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on, *vol. 4, 2001, pp. 3356 – 3363 vol.4.*
50. *T. Wimbock, D. Nenchev, A. Albu-Schaffer, and G. Hirzinger, "Experimental study on dynamic reactionless motions with dlr's humanoid robot justin," in* Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on, *oct. 2009, pp. 5481 –5486.*
51. *J. E. Pratt, "Exploiting inherent robustness and natural dynamics in the control of bipedal walking robots," Ph.D. dissertation, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA, 2000.*
52. *G. A. Pratt, "Low impedance walking robots,"* Integrative and Comparative Biology, *vol. 42, no. 1, pp. 174–181, 2002. [Online]. Available: http://icb.oxfordjournals.org/content/42/1/174.abstract*
53. *E. P. Gardner, J. H. Martin, and T. M. Jessell, "The bodily senses," in* Principles of Neural Science, *4th ed., E. R. Kandel, J. H. Schwartz, and T. M. Jessell, Eds. McGraw-Hill, 2000.*
54. *E. Torres-Jara and G. Gomez, "Fine sensitive manipulation," in* Australasian Conference on Robotics and Automation, *Canberra, Australia, 3-5 December 2008.*

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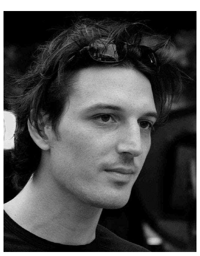

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His research interests range from vision and tactile sensing to software architectures for robotics. He has been involved as co-PI in several EU funded projects (CHRIS, Walkman, Xperience, TACMAN, KOROIBOT and WYSIWYD) and he is author and co-author of more than 100 papers in international peer-reviewed journal and conferences. He served as Program Chair of ICDL-Epirob 2014 and has been associated editors of international conferences (RO-MAN, ICDL-Epirob, Humanoids) and journals (RA-L, IJHR, IJARS and the Humanoid Robotics specialty of frontiers in Robotics and AI).