Planning Trajectories for Dexterous in-Hand Micro-Manipulation using Adhesion Forces

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***Abstract*— Micro-manipulation and micro-assembly techniques play today a key role in the development of new integrated smart systems that can find applications in strategic fields such as transport, telecommunication, health and defense. However, the existing micro-handling solutions lack of speed, flexibility and autonomy which represents an obstacle to the development of these technologies. Our approach consist in developing local micro-manipulation techniques using dexterous micro-hands. This paper focuses on the trajectory generation of a dexterous micro-hand to achieve automated repositioning and shows major differences between macro-hand and micro-hand. The first simulation results show that original trajectories, able to perform dexterous micro-manipulation in presence of adhesion forces, can be generated in about a second.**

I. Introduction

Robots manipulators at the macro-scale have different designs depending on the location of the actuated joints: i) a robotic arm with a sufficient number of Degrees of Freedom (DOF) and a basic gripper; ii) a basic arm with a dexterous hand or; iii) a redundant arm and a dexterous hand. At this scale, the most common industrial architecture is the first one. Using dexterous hands usually aims at improving the versatility and the accuracy of the robot [1] and tries to approach the human dexterity [2] [3].

Contrary to the macro-scale, micro-manipulations are usually limited to simple pick and place operations [4] [5]. Accurate multi-axes rotational positioning of micro-objects is particularly difficult to obtain which limits the possible micro-assembly operations [6] [7] [8]. Since it is not trivial to obtain multi-DOF arms able to perform rotations at the micro-scale, we are proposing to use a basic arm (translation micro-stages for instance) and a dexterous hand composed of translating fingers [9] [10].

Another characteristic related to manipulation at the micro-scale is the presence of surface forces which predominate gravitational and inertial forces. These sticky forces, caused by Van der Waals, electrostatic and capillarity forces, have been considered by the micro-robotics community for more than a decade as perturbation forces and tried to get rid of them. Indeed, the manipulated micro-objects stick to substrate during the grasping (a high pull-off force has to be applied) and stick to the gripper during the release [11]. As these forces make the automation difficult, micro-manipulation operations are often done manually [12]. This solution is usually not satisfactory as the number of micro-system units to produce is usually huge.

Contrary to various approaches that try to minimize this effect in order to fallback to dexterous manipulation at the macro-scale [13] [14], we propose in this paper to exploit these adhesion forces that can contribute to the stability of the object during the manipulation. Indeed, previous experiments have shown that a single finger can be sufficient to have a stable grasp (Fig.1).

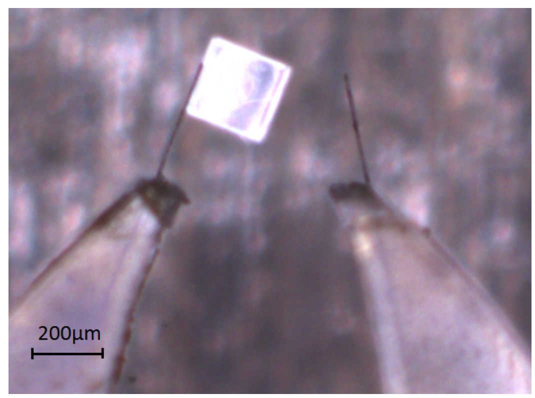

Fig. 1: Illustration of the adhesion effect: only one finger is required to have a stable grasp

As the dominant forces and the application of dexterous robotic manipulation are different at the micro-scale compared to the macro-scale, these differences have to be taken into account to develop feasible and successful dexterous micro-manipulation. The main contribution of this paper is the study of the impact of adhesion forces on grasping micro-objects and the development of a trajectory planner for in-hand dexterous micro-manipulation where original fingers trajectories are proposed.

The next Section gives an overview of the in-hand micro-manipulation problem while Section III gives a general formalization of this problem. Section IV details our methodology to compute stable grasps and generate trajectories. Finally, Section V presents some trajectories for three fingers manipulation with and without adhesion in the case of planar objects.

II. Problem Definition

In-hand manipulation refers to the ability to manipulate an object, in translation or in rotation, with multiple fingers. At the macro-scale in-hand manipulations can be achieved in different ways: by rolling [15], sliding [16] or finger gaiting

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[17]. Conversely, in-hand micro-manipulation are way more difficult to realize. For instance, controlled slip at micro-scale may be very complicated because of the importance of tactile sensing for such manipulations. Thus, we choose to restrict in-hand micro-manipulation in this paper to rotations performed using rolling without sliding and finger gaiting.

Furthermore, macro-manipulation is largely focused on designing anthropomorphic hands and on the grasping problematic. Thus, macro-hands must be very versatile in order to grasp quickly unknown objects contrary to the micro-hands which can be designed to manipulate well known rigid objects. Indeed, we assume that, in micro-assembly, components are fully characterized and the objective is to correctly orientate and position the different rigid parts to successfully realize the assembly. Thus, we choose to generate trajectories for well known rigid micro-objects.

Moreover, as the inertial forces are negligible compared to the adhesion forces at micro-scale, it is possible to consider the micro-manipulation process under a quasi-static assumption. Thus, the manipulation process is a succession of stable states.

Finally, physics of the micro-scale induce two problematic for the manipulation process. The first one is that adhesion forces can be viewed as a stabilizing effect on the grasping part. The second one concerns the finger gaiting problem as, to perform high amplitude rotations, finger reconfigurations may occurs. However, at micro-scale, removing a finger requires to apply a pull-off force which may disturb the grasp.

III. Modeling and background

As this article emphasis on the differences between macro and micro-manipulation, firstly we are going to show how the formalization of manipulation is impacted when considering adhesion forces.

A. Grasping Forces

Let us consider the general case of six DOF manipulation using N fingers. In order to manipulate the object, fingers must exert a grasping force on the object surface. The most common modeling of the contact forces at the macro-scale is the *Coulomb law*. This means that, as far as the contact force lies in a three dimensions cone there is no slippage:

$$\sqrt{f_{t_1}^2 + f_{t_2}^2} \leq \mu f_n \quad (1)$$

where f_{t_1} and f_{t_2} are tangential component of the force, f_n is the normal component parameter andμ is the friction coefficient.

Furthermore, in the case of micro-manipulation, this contact law is slightly modified. Indeed, adhesion is a stabilization factor and has an impact on the friction cone. Let us consider that the adhesion force between a finger and the object is f_{po}. Then, the Coulomb law can be rewritten as follows:

$$\sqrt{f_{t_1}^2 + f_{t_2}^2} \leq \mu (f_n + f_{po}) \quad (2)$$

The adhesion force moves the friction cone as depicted in Fig.2. Thus, contrary to the macro-scale, where only positive grasping forces can be applied (push the object), at micro-scale, it is possible to apply negatives grasping forces (pull the object) as long as the force lies in the modified friction cone.

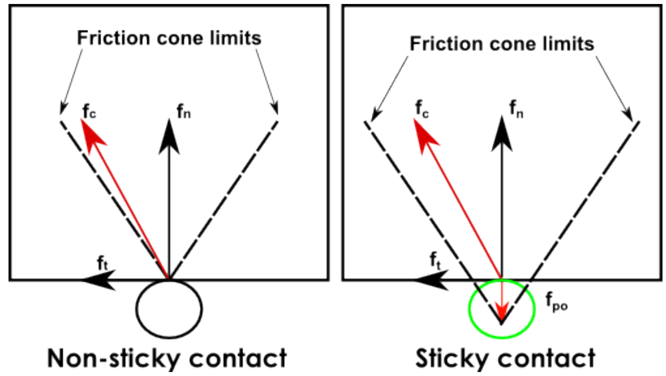

Fig. 2: Side view illustrating the impact of adhesion on the friction cone.

B. Equilibrium

When N fingers grasp an object, all the contact forces must be balanced in order to put the object at equilibrium. Thus, the following equation must be satisfied:

$$-w_{ext} = G.f_c = \sum_{i=1}^{N} w_{c_i} \quad (3)$$

where w_{ext} is the external wrench (force and moment) applied on the object (for example the weight), the matrix $G \in \Re^{6\times 3N}$ is called the grasp matrix [18] which depends on the contact position, $f_c \in \Re^{3N}$ is the vector containing the N grasping forces and $w_{c_i} \in \Re^6$ is the i^{th} grasping wrench.

The equilibrium problem is then equivalent to finding a set of forces f_c verifying Eq.3 with the non-slippage constraint defined by Eq.2. These constraints can be used to rewrite the equilibrium problem considering the limits of the friction cones. Indeed, in the case of six DOF manipulation, the resulting wrench applied on the i^{th} contact is a linear combination of j wrenches that approximate the three dimensions cone:

$$\begin{cases} w_{c_i} = \sum_j \alpha_{i,j}.w_{l_{i,j}} + \beta_i.w_{po_i} \\ \alpha_{i,j} \geq 0 \\ \beta_i \geq 0 \end{cases} \quad (4)$$

where $w_{l_{i,j}}$ is one wrench that approximate the i^{th} friction cone, w_{po_i} the wrench induce by adhesion forces, and $\alpha_{i,j}$ and β_i coefficients which must be positives to stay inside the friction cone. In the case particular case of macro-manipulation, w_{po_i} is equal to zero. Then, the equilibrium problem for N fingers can be rewritten as a function of the N friction cones:

$$-w_{ext} = \sum_{i=1}^{N} w_{c_i} = \sum_{i=1}^{N} \left(\sum_j \alpha_{i,j}.w_{l_{i,j}} + \beta_i.w_{po_i} \right) \quad (5)$$

Thus, the equilibrium problem is equivalent to find a set of $(\alpha_{i,j}, \beta_i)$ positive (not all of them null) verifying the previous equation.

Since inertial forces are negligible, the sufficient condition to perform stable micro-manipulation is that the manipulated object must be at the equilibrium at each step of the manipulation sequence.

Moreover, the reconfiguration problem is similar to the equilibrium problem. Indeed, to remove a finger the remaining contact must resist the external pull-off force f_{po} applied on the removing contact. This means that reconfiguration problem is equivalent to finding f_c such that

$$-w_{ext} - w_{po} = G.f_c \quad (6)$$

where w_{po} is the wrench induced by the release of one of the contacts. Obviously in this case the matrix G is in $\Re^{6\times3(N-1)}$ and f_c in $\Re^{3(N-1)}$ and this problem can also be expressed as function of the friction cones.

IV. Dexterous Manipulation with Adhesion Forces

As stated in the previous section, we assume that the manipulated objects are well known, and the computing of all the contact configurations which verify equilibrium is thus possible. Consequently, equilibrium positions are going to be the starting point of our trajectory planning which consist in navigating between stable configurations from an initial position to a final position. Then, the trajectory planner defines the finger trajectories required to rotate along a defined angle, starting from the initial configuration.

A. Equilibrium and Reconfiguration Maps

In the case of neglected external perturbation ($w_{ext} = 0$), one way to verify if a configuration of N contacts can verify equilibrium, is to test if the convex hull formed by the friction cones wrenches ($w_{l_{i,j}}$) contains the origin of the wrench space [19]. Thus, when external perturbations are considered the existence of a solution is equivalent to testing if the convex hull contains the external wrench.

Then, it is possible to create several sets (maps) which depict all the equilibrium configuration with regards to the number of contacts:

$$M_k = \Big\{ (c_1,..,c_k) \in \Re^{(3\times k)} \mid -w_{ext} \in Convhull(w_{l_{1,1}},\dots,w_{l_{k,j}}) \Big\} \quad (7)$$

where k is the number of contacts, c_k is a vector containing the contact coordinates on the object surface and $Convhull(w_{l_{1,1}},\dots,w_{l_{k,j}})$ represent the convex hull.

Figure 3 gives a representation of one of the M_k sets in the case of a planar circle without external perturbations. Contact position are sorted using curvilinear abscissa. The depicted areas represent the equilibrium configurations in the case of a two fingers grasp without any adhesion forces at the contact. Obviously such type of sets are symmetric.

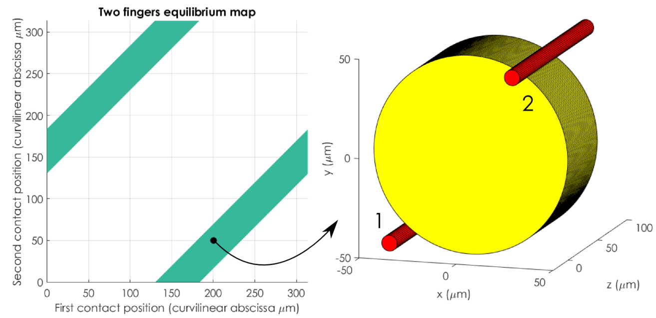

Fig. 3: Representation of the set M_2 (equilibrium map) for a circle, without considering adhesion forces (non-sticky behavior, $\forall i, w_{po_i} = 0$)

Furthermore, when finger gaiting is required another map is needed: the reconfiguration map. This set is directly related to the ability to remove a finger from the object. Consider a N fingers grasp on which the last finger must be removed and note w_{po} the resulting wrench induced by the adhesion forces. This configuration is said reconfigurable when w_{po} is included in the convex hull formed by the friction cones' wrenches of the $N-1$ remaining contacts. This can be formalized as follows:

$$D_k = \Big\{ (c_1,..,c_k) \in \Re^{(3\times k)} \mid (c_1,..,c_{k-1}) \in M_{k-1}, -w_{po,k} \in Convhull\left(w_{l_{1,1}},\dots,w_{l_{k-1,j}}\right) \Big\} \quad (8)$$

For each M_k ($k > 1$), it is possible to define a corresponding D_k. Figure 4 (left) shows all the reconfiguration positions for a defined third contact location in the case of a three fingers grasp. A non-reconfigurable position is also represented in Fig.4 (right). In this particular case, the stability cannot be ensure so this configuration cannot be used for manipulation.

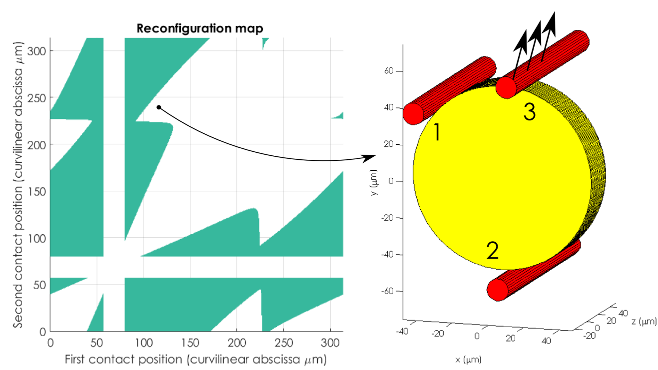

Fig. 4: Representation of the set D_3 (reconfiguration map) for an assigned location of the third contact considering adhesion (sticky behavior, $\forall i, w_{po_i} \neq 0$).

B. Trajectory Generation

1) Representation: All the M_k and D_k maps can be seen as graph where every equilibrium position is a node. The goal is to move in and between the different maps to realize the desired movement. More particularly, navigating through a M_k map is considered as a direct manipulation of the object whereas navigating between two sets M_i and M_j is considered as finger gaiting. In this case, the reconfiguration map D_k are also part of the graph. Each node in D_k is specifically used to link two adjacent sets (M_k and M_{k-1}) when a finger is removed. Moreover, as adhesion does not perturb the grasp when adding a finger, the link between M_k and M_{k+1} is direct.

Thus, the initial configuration is represented as a specific node in one of the maps. Moreover, as only rolling is considered, the in-hand manipulation can be seen as the required rolling distance to perform the desired rotation. Hence, the goal node is not unique and we need to define the optimal trajectory.

2) Navigation: In order to plan our trajectory we must define the way to navigate in the different maps. In the case of manipulation through rolling, a node in M_k is not connected to all the neighboring nodes (also in M_k). Indeed, in order to manipulate an object with N contacts using rolling without sliding, it is required that all fingers roll of the same amount and in the same direction on the object surface. Consequently, the rolling constraint induces a unique available path in a M_k map (depending on the radius of the fingers). Thus, each node in M_k has only two neighbors in the same map.

Then, when navigating between maps two cases can occur: adding a finger or removing a finger. When adding a finger, which is equivalent to switching from M_k to M_{k+1}, the current node is connected to all the configurations with an extra contact included in M_{k+1}. When removing a finger, the current node, using k fingers, is connected to all the configurations composed with $k-1$ fingers and with the current node included in D_k.

3) Algorithm: One popular way to search through a graph is the A^* algorithm. This heuristic graph search algorithm provides complete and optimal path between the initial and the goal node. A^* has been used in micro-manipulation [20] and also in micro-assembly [21] but based on our knowledge it has not been used for planning in hand manipulations. We chose to implement an A^* algorithm for our trajectory planner in order to obtain optimal solutions.

An important part of the graph search is the cost function used to connect two nodes. Considering the way we can navigate through the graph, we define three cost functions corresponding to the three possible actions: rolling, adding a finger and removing a finger.

For the first case (rolling), the cost function is defined as the rolling distance needed to go from the current node to the next one. This distance is the arc length between two positions on the object surface and is noted $L_r(Node(i), Node(f))$.

When adding a finger, the cost function can take two values: (i) if the finger has not been used previously, then the cost function will be a non zero constant C_a. This value allows to estimate the traveled distance from the previous position to the new one. (ii) if the finger has been used previously, then the cost function will be an estimation of the distance between the last contact position and the new one ($L_r(Node(prev), Node(new))$ plus C_{a_r} a non zero constant).

Moreover, A^* algorithm requires defining an admissible heuristic. As the in hand manipulation is a rotation it is possible to define the heuristic as the remaining rotation from the current node. Moreover, as rolling is used to rotate the object it is also possible to define the heuristic as a distance. Indeed, consider that the finger used for the manipulation has a radius r_d and that rot is the rotation amplitude in radians. Then, at the initial node, the heuristic will be $d_{rot} = r_d \times rot$. Obviously this heuristic never overestimates the distance to the goal so it is an admissible heuristic.

V. RESULTS

The methodology presented in the previous section has been implemented and tested to generate trajectories for planar objects. Moreover, in micro-assembly most of the objects made in micro-fabrication are planar objects so the results presented here are still interesting in the application framework.

A. Impact of Adhesion on Equilibrium and Reconfiguration Maps

First of all, we are going to show the effect of the adhesion forces on the maps (M_k and D_k) used for the trajectory generation. As an example, we consider the M_2 map described in Fig.5 to show the impact of adhesion on the equilibrium configurations. Note that this map correspond to the object depicted in Fig.7

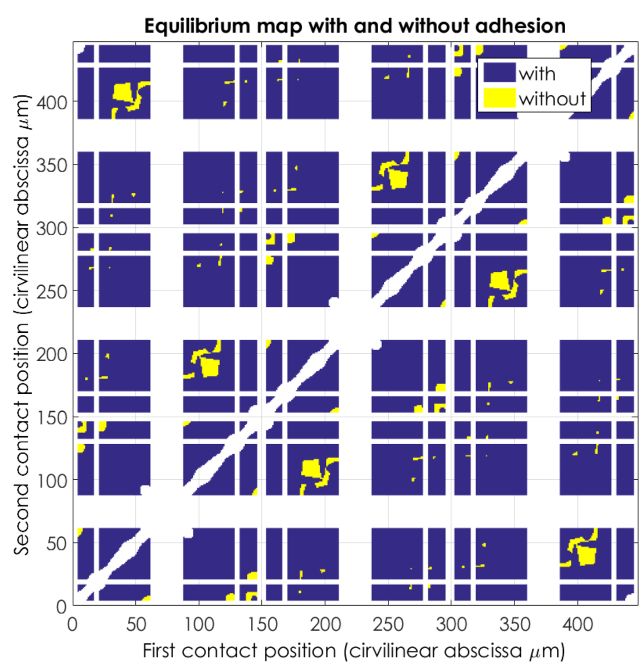

Fig. 5: Representation of the set M_2 (equilibrium map) with and without adhesion for an arbitrary shaped object depicted in Fig.7.

Figures 5 shows the stabilizing effect of the adhesion on an arbitrary shaped object. For this example, we used uniform friction value on the surface ($\mu = 0.3$), an adhesion force of 1 μN, a neglected external wrench and fingers with a radius of 3.5 μm. The yellow areas correspond to the contact configurations where it is possible to obtain equilibrium without adhesion. As predicted, the area is significantly bigger when adhesion is considered. This means that there is more possibility to manipulate the object when adhesion is used.

Moreover, Fig.6 shows the reconfiguration nodes for a defined removed finger. It can be seen that, without adhesion, all the stable configurations with two fingers are also admissible reconfiguration nodes. In contrast, with adhesion, there is fewer reconfigurations positions compared to the stable configurations. Thus, with adhesion, more trajectories are available in a defined M_k map (Fig.5) but reconfiguration are a limiting factor.

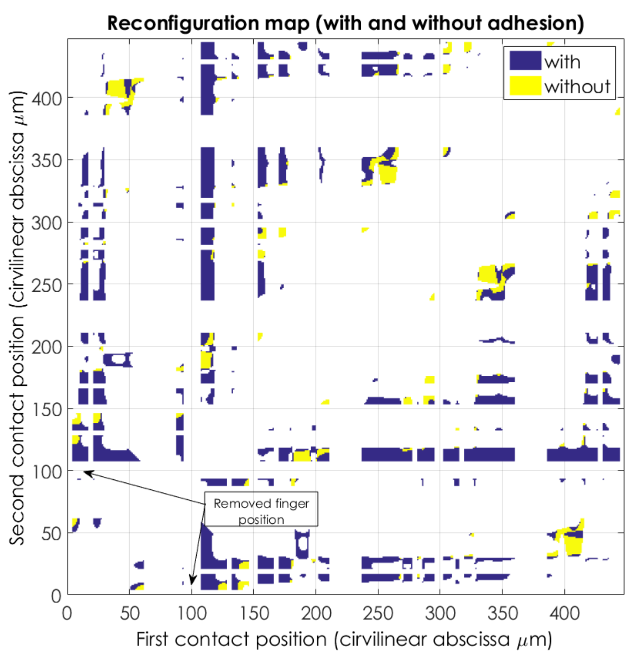

Fig. 6: Representation of the set D_3 (reconfiguration map) with and without adhesion on a an arbitrary shaped object depicted in Fig.7.

B. Impact of Adhesion on Trajectory Generation

We consider the case of an in hand manipulation with a maximum of three fingers. This means that the nodes are represented by M_1, M_2, M_3 for manipulation and D_2 and D_3 for reconfiguration. All the following results have been generated using the same parameters presented in the previous section.

Figure 7 illustrates the computed trajectory for a 130° rotation with adhesion. As shown by Fig.7a, the initial configuration is a grasp with only two fingers. From this configuration, the optimal path to realize the rotation is a two fingers manipulation.

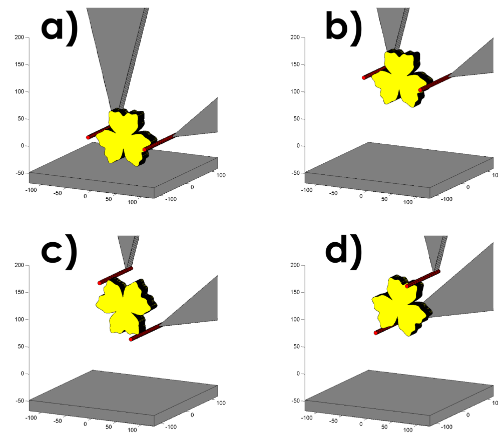

Fig. 7: Images sequence describing the clockwise trajectory generated by the planner for a 130° rotation considering adhesion phenomena.

Figure 8 shows a trajectory for the same rotation but without considering the adhesion phenomena. It can be seen that for the same rotation amplitude the manipulation sequence is more complex in this case. Indeed, three fingers are required and finger gaiting step occurs because of the friction limits.

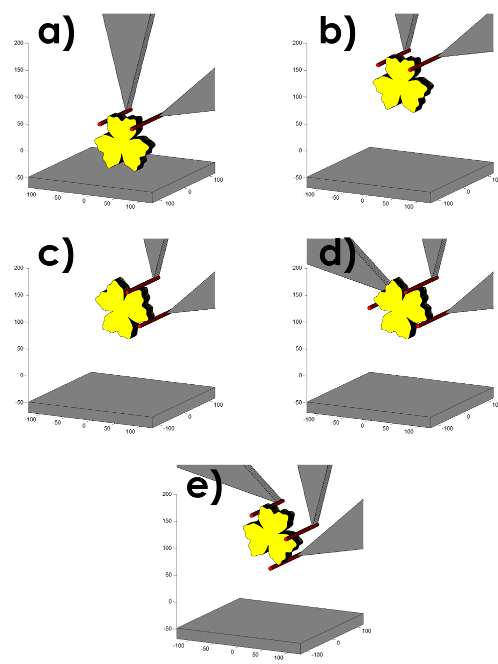

Fig. 8: Images sequence describing the clockwise trajectory generated by the planner for a 130° rotation without considering adhesion phenomena.

The previous trajectories seem to show that with adhesion the manipulation process is faster. A statistical analysis has been performed to confirm this impression. For each case (with and without adhesion) 250 trajectories were generated and the cost of each trajectory were computed. This cost, based on the cost function and on the heuristic described in the previous section, estimate the traveled distance by the finger during the manipulation.

Figure 9 shows this statistical results for the arbitrary shaped object. For each rotation amplitude it can be seen that the manipulation process is always faster when considering adhesion phenomena. Thus, taking advantage of adhesion effects have a positive impact on the manipulation process.

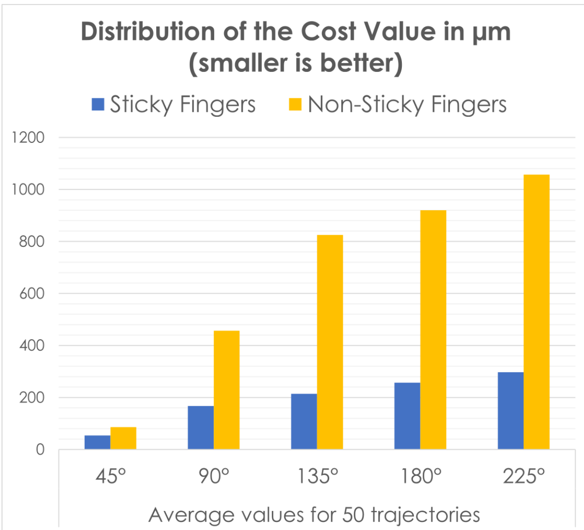

Fig. 9: Chart representing the distribution of the trajectory cost value for various rotation amplitudes and condition of use. For each rotation amplitude and each case fifty rotations were generated.

VI. Conclusion

In this paper, a trajectory planner for dexterous micro-manipulation taking into account adhesion forces was presented. This planner is based on a A^* algorithm in order to generate optimal trajectories (relative to cost functions) and take into account the specificity of the micro-scale: the adhesion phenomena.

Our planner was validated in simulation considering different conditions of use. The results show that in-hand micro-manipulation is significantly different than macro-manipulation. Thus, original trajectories were generated. Adhesion phenomena cannot be neglected and we showed that it can be useful in the manipulation process. Moreover, even if the adhesion is not fully predictable this planner can be used to generate trajectory in the worst cases (*i.e* considering grasping without adhesion and considering reconfiguration with adhesion).

The next step of this work will involve optimization of the contact forces on the generated trajectory and implementation of these new trajectories on an experimental micro-manipulation setup developed in our laboratory [22]. In addition, as the problem was formalized for three dimensions in-hand micro-manipulation, the current planner will be extended to non-planar objects and manipulations.

Acknowledgment

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