Orienting Micro-Scale Parts with Squeeze and Roll Primitives*

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Abstract

Orienting parts that measure only a few micrometers in diameter introduces several challenges that need not be considered at the macro-scale. First, there are several kinds of sticking effects due to Van der Waals forces and static electricity which complicate hand-off motions and release of a part. Second, the degrees of freedom of micro-manipulators are limited. This paper presents a complete algorithm that addresses these challenges. We will show that a sequence of simple manipulation operations can uniquely orient an asymmetric part without sensing. This allows us to apply the same plan to many (identical) parts simultaneously. For asymmetric parts we can find a plan of length $O(n)$ *in* $O(n)$ *time that orients the part, where* n *is the number of vertices.*

1 Introduction

Increased miniaturization of mass-produced consumer and industrial products such as disk drives, cameras, displays, and sensors will require fundamental innovations in parts handling. Conventional “pick-and-place” techniques do not work well at the micro-scale where sticking affects dominate. We will use the term ‘sticking effects’ to describe the combined effect of Van der Waals forces, electrostatic surface charges and other attractive forces that occur at the micro-level. Due to these sticking effects parts can stick to a manipulator without being grasped. The attractive forces drop rapidly in magnitude as the distance between the part and manipulator increases. An additional complication for handling micro-parts is that the sticking effects vary wildly, even if all the material properties and geometries of the objects involved are known. In order to manipulate micro-parts, we propose manipulation strategy that consists of applying simple operations requiring no more than two degrees of freedom. During an operation one degree of freedom will be active and the other will be compliant in order to maintain contact with the part. We maintain complete control over the part’s orientation.

Figure 1 illustrates a plan that orients a part by rolling and squeezing it between two horizontal micro-scale jaws. Note that for this type of manipulation we only need to consider the convex hull of the part. Initially the part can be in any orientation, but after execution of the plan the part will be in one of two orientations. The state transitions after each operation are indicated by the dashed lines.

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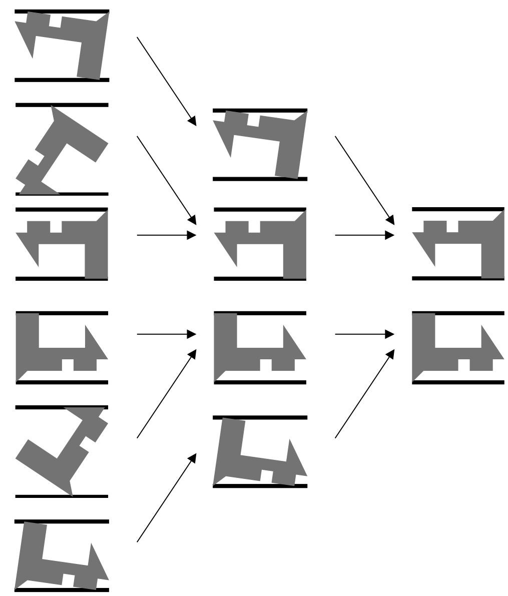


Figure 1: Example of a squeeze-roll plan orienting a polygonal part. After the initial operation the part is in one of six orientations. After two more sensorless operations the part is oriented up to 180° symmetry.

2 Related Work

2.1 Micromanipulation

When parts are smaller than one millimeter the effect of adhesive forces becomes significant. Fearing (1995) gives an overview of all the different adhesive forces that occur at this scale. Many researchers have worked on reliable pick and

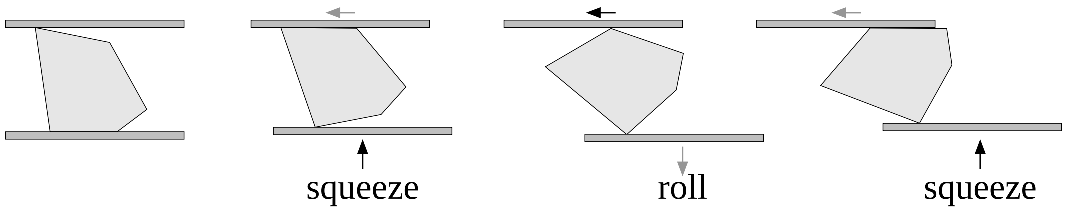
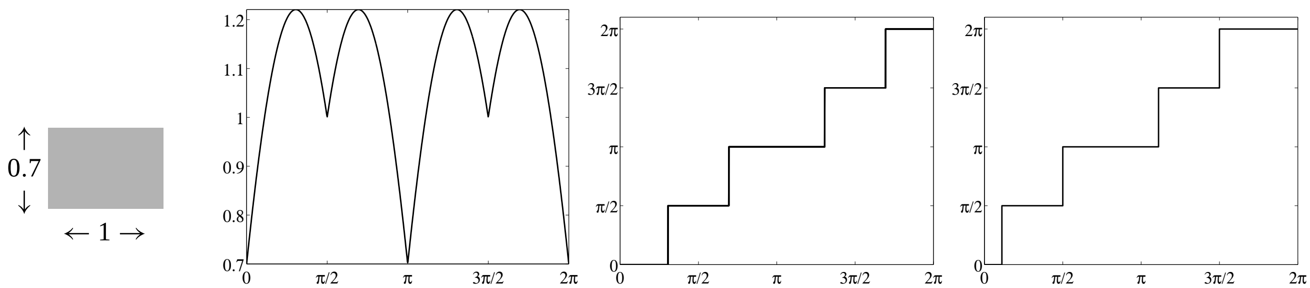


Figure 2: A sequence of micro-manipulation operations, from left to right. We automatically follow each roll by a squeeze. The small arrows indicate in which direction the jaws have moved during each operation. The black arrows indicate a controlled motion, the gray arrows indicate a compliant motion. Note that parts always remain in contact.



(a) A rectangular part (b) Its diameter function (c) Its squeeze function (d) Its roll function with upper jaw translating 1 unit to the left

Figure 3: The diameter, squeeze and roll functions. Note that the squeeze and roll functions are monotone.

place operation of micro-scale object. Miyazaki and Sato (1996) and Saito et al. (1999) describe a system where a needle is used to assemble 3D structures composed of particles ranging from 10nm to 1μm in size. The sticking effects enable the needle to pick up a particle. By translating along a so-called shearing trajectory the needle releases the particle. A human operator controls the manipulator, while a scanning electron microscope (SEM) provides the visual feedback. Koyano and Sato (1996) describe a similar system for pick-and-place operation. They use two different sized needles and define different part release motions. One motion consists of clamping the part onto a surface with a thin needle, while the large needle releases the part. The sticking effects are not large enough to make the part stick to the thin needle. Another part release motion consist of rotating the needle around the part in order to minimize the contact area. Zesch and Fearing (1998) explore how one can orient parts by pushing them with an AFM cantilever equipped with a force sensor. The force sensor is used to detect obstacles and changing contact conditions. In (Shimada et al., 2000) a system is described consisting of two orthogonal one degree-of-freedom tweezers. The tweezers are equipped with force sensors. Shimada et al. describe two different ways to orient the part with these tweezers: one way is to roll the part between them, another is to pivot the part around a fixture. *(Shimada et al., 2000) contains a lot more good micro-manipulation references…*

2.2 Parts Orienting

The problem of how to bring parts into a desired orientation has been well studied at the macro-scale. It is not necessary to grasp an object in order to orient it. Mason (1982, 1985) showed how to orient parts by pushing them. This can be used to design a sequence of fences over a conveyor belt (Peshkin and Sanderson, 1988; Wiegley et al., 1996; Berretty et al., 1998). Akella et al. (1997) showed that instead of a sequence of fences one can also use one fence with one rotational degree of freedom. pushing

Goldberg (1993) showed that it is possible to orient polygonal parts with a frictionless parallel-jaw gripper without sensors. Goldberg conjectured and Chen and Ierardi (1995) proved that for every n-sided polygonal part, a sequence of 'squeezes' can be computed in $O(n^2)$ time that will orient it up to symmetry. The length of such a sequence is $O(n)$. Akella et al. (2000) that with partial sensor information the length of this sequence can be reduced to $O(m)$, where m is the maximum number of states with the same sensor value. squeezing

Bicchi and colleagues showed that by simply rolling an object between the two hands of a parallel-jaw gripper it is possible to orient and position polyhedral parts (Ceccarelli et al., 2000; Marigo et al., 1997) and smooth 3D parts (Marigo and Bicchi, 2000). The jaws are equipped with tactile sensors, which allows the system to reconstruct the shape of unknown smooth objects (Bicchi et al., 1999). rolling

In (Rao et al., 1995) an algorithm is described to orient polyhedral parts using so-called pivot grasps. A part is pivoting grasped with two hard finger contacts and is then free to rotate around the axis formed by the contacts.

tilting Erdmann and Mason (1988) developed a tray-tilting sensorless manipulator that can orient planar parts in the presence of friction. If it isn't possible to bring a part into a unique orientation, the planner would try to minimize the number of final orientations. In (Erdmann et al., 1993) it is shown how (with some simplifying assumptions) three-dimensional parts can be oriented using a tray-tilting manipulator. In particular, for polyhedral parts with n faces a sequence of 'tilts' of length $O(n)$ can be found in $O(n^3)$ time. Zumel (1997) used a variation of the tray tilting idea to orient planar parts. Zumel used two actuated arms connected at a hinge to tilt parts from one arm to the other.

vector fields In recent years a lot of work has been done on programmable force fields to orient parts (Böhringer et al., 1997, 1999; Kavraki, 1997; Reznik et al., 1999) The idea is that some kind of force 'field' (implemented using e.g. MEMS actuator arrays) can be used to push the part in a certain orientation. Kavraki (1997) presented a vector field that induced two stable configurations for most parts. Böhringer et al. used Goldberg's algorithm (1993) to define a sequence of 'squeeze fields' to orient a part. They also gave an example how programmable vector fields can be used to simultaneously sort different parts and orient them.

3 Two Micro-Manipulation Primitives

We manipulate parts with a pair of parallel jaw grippers. We assume there is no slip between the jaws and the part. We can realize this assumption, for instance, by making the part and jaws out of a hydrophobic material and embedding them in a fluid. We also assume both jaws will always be in contact with the part and that there are no sudden changes in the pose of the part due to sticking effects. One jaw can translate in the horizontal direction, the other jaw can translate in the vertical direction. With each pair of grippers we can perform the following two operations:

Squeeze We close the jaws and, simultaneously, allow the jaw that can translate in the horizontal direction to move compliantly until a stable grasp is reached. This is equivalent to a frictionless jaw grasp (Goldberg, 1993).

Roll We translate one jaw in the horizontal direction by a given amount and allow the other jaw to move compliantly. To make sure that the part is always in one of a finite number of orientations, we automatically follow each roll by a squeeze.

These two operations are illustrated in figure 2. These operations can be defined more formally as functions that map orientations to orientations. Let S^1 be the set of orientations

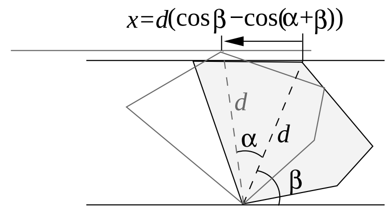


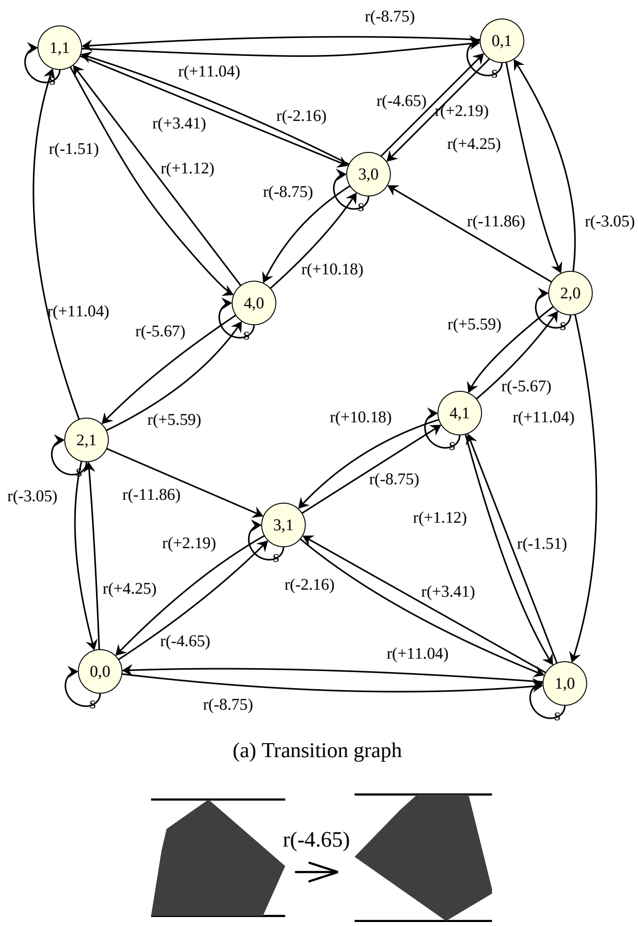
Figure 4: Relationship between x, the translation of the upper jaw, and α, the change in orientation during a roll operation.

in the plane. Consider the *diameter function* $d : S^1 \to \mathbb{R}$, which, given an orientation, returns the distance between the jaws when they just touch the part in this orientation. We define the *squeeze function*, $s : S^1 \to S^1$, such that if θ is the initial orientation, $s(\theta)$ is the orientation after the squeeze is completed. Note that for any θ $s(\theta)$ is a local minimum of the diameter function.

For the roll operation we can define a parametrized family of functions, $r_x : S^1 \to S^1$, such that if θ is the initial orientation, $r_x(\theta)$ is the orientation after the upper jaw has been translated by x and the part has been squeezed. We define a local frame such that if x is greater than 0, the jaw moves to the left. A roll function corresponds roughly to a shifted squeeze function. Figure 3 shows these functions for a rectangular part. Suppose that during a roll the contact points do not change. For a given translation x of the upper jaw the change in orientation is then equal to $\alpha = \cos^{-1}(\cos\beta - x/d) - \beta$, where d is the distance between the contact points and β the angle between the x-axis and the line through the contact points. See figure 4. Note that x and α always have the same sign. If the contact points *do* change during a roll, we divide the roll into smaller steps such that during each step the contact points do not change. The total change in orientation is simply the sum of changes during each step. It is not hard to see that for a given amount of translation the roll function is monotone in the orientation. We will use this property later.

4 Planning Algorithm

Define a state as an edge of the part being aligned with one of the jaws. Since there are 2 jaws, an n-sided polygon can be in $2n$ states. The squeeze and roll primitives are closed under the set of part states: any primitive will map from any state to another state in the set. For each state we compute the minimum and maximum amount of translation needed to make a clockwise and counter-clockwise transition to the next stable edge. These minima and maxima correspond to critical points where the outcome of a roll operation will change. Now consider the sorted list of *all* critical points for all states. To determine all possible outcomes of a roll operation applied to a set of states, it is sufficient to look



(a) Transition graph

(b) Transition from state [0, 0] to [3, 1]

Figure 5: Each node consists of a pair $[e, j]$, where $e = 0, \ldots, n-1$ is the edge index and $j = 0, 1$ is the jaw index.

up the outcomes at all the midpoints between consecutive critical points. In other words, even though we can roll a part by any continuous value, we only need to consider a finite set of $O(n)$ roll functions. The roll and squeeze functions induce a labeled graph on the states, where each edge is labeled with the appropriate function. Figure 5 shows an example of such a graph for a given part.

Based on the roll and squeeze functions we can also construct a graph where the nodes are *sets* of states, which we will call *hyperstates*. There exists an edge from node v to v' if and only if applying a roll or squeeze operation to each state in v results in the set v'. Each edge is labeled with the corresponding operation. The goal is now to find a path in this graph from the set of all states to a set with as few elements as possible. The goal set will always have at least two elements, because we can not distinguish any two orientations that are 180 degrees apart.

We are interested in finding the shortest paths from the node representing all states to nodes with a minimal number of states. These paths correspond to plans that orient a part with the smallest number of operations. Natarajan (1989) was the first to analyze the complexity of this problem. He showed that given k functions a plan can be found, if one exists, in time $O(kn^4)$. Eppstein (1990) presented an algorithm that given k *monotone* functions finds the shortest plan in $O(kn^2)$ time. Goldberg (1993) and Chen and Ierardi (1995) improved on this bound for the special case where functions correspond to squeezes in a finite number of directions. In this case a plan of length $O(n)$ can be found in time $O(n^2)$. Recently, Berretty et al. (1998) analyzed another monotone function called the *push* function. The push function, $p_\alpha : S^1 \to S^1$, when given an orientation θ returns the orientation of the part $p_\alpha(\theta)$ after it has been pushed from direction α by a fence orthogonal to the push direction. With the push operation it is possible to uniquely orient a part. Berretty et al. presented an $O(n^3 \log n)$ algorithm to find the shortest plan.

Since we have $O(n)$ roll functions and one squeeze function, we can find a plan in $O(n^3)$. Based on the results in the next section we conjecture that for asymmetric parts the final hyperstate contains always exactly two states.

It is possible that there exist many paths of the same length that lead to nodes with the same number of states. We can impose additional constraints to find the 'best' path. For instance, we might prefer squeeze operations over roll operations. Or we can minimize the total amount of translation required by a plan. Finally, we can select the path that is the most robust.

It is possible to orient a polygonal by repeatedly applying the same operation. Consider the set of minimal distances such that a counter-clockwise roll with this distance as parameter will cause a transition to another state. Let d be a distance between the second largest and largest elements of that set. If we perform a roll operation with distance d $n-1$ times, the part will be in the state corresponding to the largest element of the set. So we can compute a plan of length $n-1$ that will orient a part in linear time.

5 Random Polygonal Parts

Figure 1 shows a plan that was found using the algorithm. The algorithm takes the convex hull of the part as input.

To get a sense for what kinds of polygons take many operations to orient, we tested the algorithm on a set of random convex polygons. Random convex polygons are generated in the following way. We can regard a convex n-sided polygon as a set of n vectors subject to the constraint that the vectors add up to the zero vector. We pick the x-coordinates (and y-coordinates) of the vectors as follows: we pick a uniformly random point inside a $n-1$ dimensional hypersphere and rotate the resulting point (padded with a zero to make its

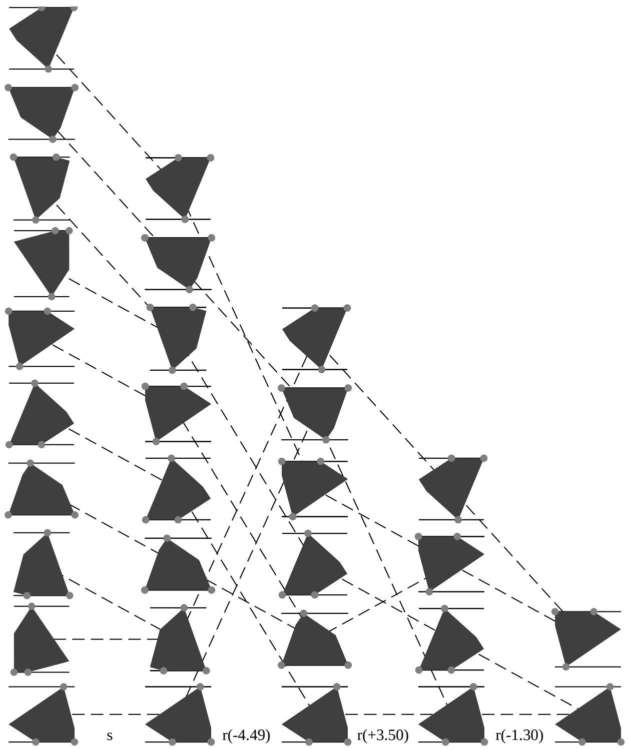


Figure 6: For parts with many stable grasps many operations are needed to orient it.

length n) to lie in the hyperplane defined by $\sum_{i=1}^{n} x_i = 0$. The vectors can be computed in $O(n)$ time. To create a polygon we need to sort the vectors by angle, causing the overall run time to be $O(n \log n)$. This algorithm is due to Lambert (1994).

In figure 6 an example is shown of a 5-sided polygon that requires 4 operations to orient it. The polygon is squeezed first, followed by three roll transitions. In general, the more stable grasps a part has, the more operations will be needed to orient it. If *all* states correspond to stable grasps, squeezing the part has no effect and only roll operations can be used to orient it.

Under the probability distribution function induced by the algorithm described above, we found that almost all random polygonal part shapes can be oriented in less than four operations. In figure 7 is shown the cumulative distribution function of the number of operations required to orient a random polygon. This function is computed by sampling 5000 polygons for a given number of nodes. From this figure it can be concluded that the expected number of operations needed is small and increases slowly with the number of nodes.

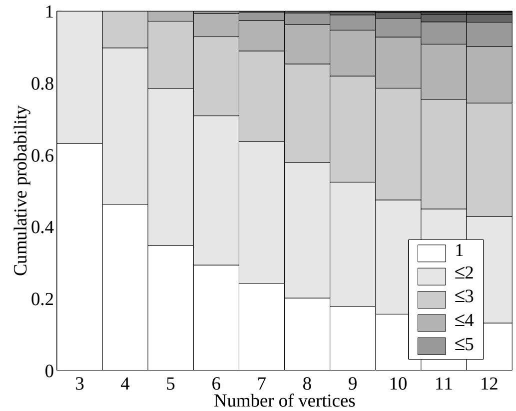


Figure 7: Plot of number of operations vs. number of nodes. Cumulative distribution function of number of operations required to orient a part with 2, 3, …, 12 nodes.

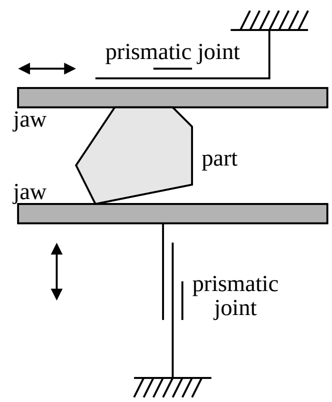


Figure 8: The kinematics of a squeeze-roll micro-gripper

6 Discussion

We have presented a complete algorithm that computes a plan to orient a polygonal part at the micro-scale. The manipulation primitives take into account the sticking effects that occur at the micro-scale as well as the limited degrees of freedom that manipulators typically have at that scale. The part orienting strategy is completely sensorless.

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